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13. ABSTRACT *(Maximum 200 words)*

The purposes of this conference were: (1) to bring together scientists and engineers from academia, government laboratories, and industrial laboratories to examine the critical issues of incorporating mesoscopic devices into real device systems, (2) to establish those areas where research and developement focus efforts are needed to examine critical issues in the interfacing of mesoscopic devices with systems, and (3) to identlfy fundamental technology and scientific issues which may limit the development of mesoscopic devices in real systems. These purposes were accomplished by assembling approximately 100 of the most prominent researchers in this area in order to discuss these critical issues. The meeting was held 24-29 April 1994, in Kona, Hawaii.

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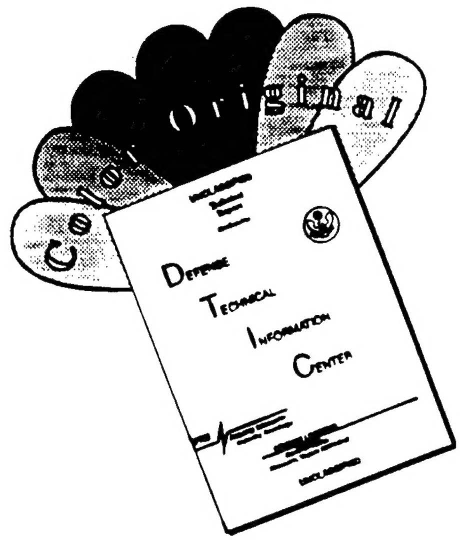

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Final Report on the Conference

Surface and Interfaces of Mesoscopic Devices

I. Introduction

The purposes of this conference were: (1) to bring together scientists and engineers from academia, government laboratories, and industrial laboratories to examine the critical issues of incorporating mesoscopic devices into real device systems, (2) to establish those areas where research and development focus efforts are needed to examine critical issues in the interfacing of mesoscopic devices with systems, and (3) to identify fundamental technology and scientific issues which may limit the development of mesoscopic devices in real systems. These purposes were thought to accomplished by assembling approximately 100 of the most prominent researchers in this area in order to discuss these critical issues. The meeting was held 24-29 April 1994, in Kona, Hawaii, under the direction of Dr. David K. Ferry (Arizona State University) and Dr. Karl Hess (University of Illinois at Urbana-Champaign).

II. Motivation for the Conference

Over the past few years, considerable attention has focused upon mesoscopic devices, the physics and fabrication of these devices, and upon the possibilities that these may prove fruitful for future microelectronics. However, most of the work up to the time of the conference has focused upon the properties of the devices, just as reduced dimensional bulk quantitites, and there was not much focus upon the true role that interfaces, surfaces, contacts, etc., play upon the operation and/or physics of the devices. For this reason, a conference was held on the subject of surfaces and interfaces of mesoscopic devices.

The need for such a conference was evident in the fact that, as we approach the expected end of Si CMOS scaling, with gate dimensions in the 0.5-0.7 micron regime,

new architecture and circuitry are expected to be needed for the introduction of mesoscopic devices based upon more quantum functionality. In these small structures, however, the surface (and/or interface) to volume ratio is quite high. It is now recognized, both from experimental studies of such mesoscopic devices and from the recognition that small devices are dominated by their boundaries, that the actual performance and operation of such quantum functional devices will be dramatically affected by these interfaces and surfaces. In fact, one over-riding problem in the area may be summarized by the observation that truly small device structures don't work, and it is necessary to overcome this problem.

In spite of these recognitions of the role of surfaces and interfaces in mesoscopic devices, little attention had been given to studies of these surfaces and interfaces, or to studies aimed at gaining control of these quantities. The purpose of this workshop was to bring together key individuals within the research community in order to focus upon, and identify critical issues for, the development of functional quantum mesoscopic devices. It was the intent of this workshop to focus not only upon the theoretical and experimental aspects of the interaction between surfaces and interfaces and the internal physics of transport, but also upon the effect processing has in creating particular states/environments at the surface and interface.

III. Organization of the Workshop

The organizing committee was composed of major experts in the field, who worked to select an outstanding group of speakers, both of invited papers and of contributed papers. This committee was composed of:

Dr. David K. Ferry, Regents' Professor, Arizona State University, Chair

Dr. Karl Hess, Professor, University of Illinois at Urbana-Champaign, Co-Chair

Dr. Steven Goodnick, Professor, Oregon State University

Dr. Tom McGill, Fletcher Jones Professor, California Institute of Technology

Dr. Mark Reed, Professor, Yale University

Dr. Michael Stroscio, The Army Research Office

The program (attached) was a combination of invited and contributed speakers. The invited speakers were:

Dr. John Barker, University of Glasgow

Dr. Randy Feenstra, IBM Watson Research Center

Dr. King-Wok Kim, North Carolina State University

Dr. Craig Lent, Notre Dame University

Dr. Zusanna Liliental-Weber, Lawrence Berkeley Laboratory

Dr. Joseph Lyding, University of Illinois at Urbana-Champaign

Dr. Massimo Macucci, University of Pisa

Dr. Thomas Reinecke, Naval Research Laboratory

Dr. David Ting, California Institute of Technology

These speakers emphasized the topic areas: (1) the role of interfaces in the electronic structure of mesoscopic devices, (2) the role of interfaces in transport in mesoscopic devices, (3) the characterization of mesoscopic devices, particularly in the sub-50 nm regime, (4) surface and interface analysis on the sub-50 nm scale, (5) surface and interface chemical effects of processing, (6) the use and analysis of self-assembled monolayers in mesoscopic devices, (7) materials issues for mesoscopic devices, (8) quantum transport in open, far-from-equilibrium mesoscopic devices, (9) modeling and lithography for single and arrays of mesoscopic devices, and (10) optical characterization of optical and electronic mesoscopic devices. Coupled to the invited speakers were 37 contributed papers. The total scientific content and results are contained in the abstracts of the invited and contributed papers, which are attached below.

The conference was felt to be a success by the attendees. While no follow-on has as yet been formulated, the University of California, Santa Barbara, group has

volunteered to undertake the organization of such a follow-on meeting. This is currently on hold to evaluate the scope and number of meetings on quantum functional devices and mesoscopic systems during the 1995-1996 time frame.

PROGRAM

SURFACES AND INTERFACES IN MESOSCOPIC DEVICES

April 24-29, 1994
Keauhou Beach Hotel
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PURPOSE

Over the past few years, considerable attention has focused upon mesoscopic devices, and there is growing evidence that these devices will be of importance in future ULSI. In particular, as scaling progresses to future dimensions of semiconductor devices, it is expected that gate lengths and critical dimensions will be reduced to those of interest in mesoscopic devices, that is on the scale of inelastic and elastic mean free paths. However, most of the work on mesoscopic devices has focused upon the properties of the devices as reduced dimensional "bulk" quantities, and there has not been much focus upon the true role that interfaces, surfaces, contacts, etc. play in the operation and/or physics of the devices.

In contrast to these "bulk" studies, it is now being recognized, both from many experimental studies of these mesoscopic devices and from observations that small quantum devices are dominated by their boundaries, that the actual performance of real mesoscopic devices will be dramatically affected by the interfaces and surfaces. The purpose of this conference is to bring together key individuals within the research community in order to focus upon, and identify, critical issues for the development of future mesoscopic devices. It is the intent of the workshop to focus not only on the theoretical and experimental aspects of the interaction between the surfaces and interfaces and the internal physics of transport, but also upon the effect processing has in creating particular states/environments at the surface and/or interface.

CO-SPONSORS

We wish to express our gratitude to the Office of Naval Research and the Army Research Office for their support of this conference.

Sunday, April 24, 1994

3:00 pm - 6:00 pm	Registration
6:00 pm - 7:30 pm	Dinner
7:30 pm - 8:30 pm	Opening Reception

Monday, April 25, 1994

7:00 am - 8:30 am		Breakfast
8:30 am		General Introduction David Ferry
		SESSION I - Chair: Steve Goodnick, Oregon State University
8:30 am	Ma1	"Cross-Sectional Scanning Tunneling Microscopy of Semiconductor Structures" (invited) R.M. Feenstra IBM Research Center
9:25 am	Ma2	"Interfacial Properties of InAs/$Ga_{1-x}In_xSb$ Superlattices Studied by Cross-Sectional Tunneling Microscopy" E.T. Yu and A.Y. Lew U.C. San Diego D.H. Chow and R.H. Miles Hughes Research Labs
9:55 am	Ma3	"RHEED and XPS Studies of Interfaces and Surfaces in the Mixed Anion InAs/GaSb/A1Sb Material System" M.W. Wang, D.A. Collins, R.W. Grant* and T.C. McGill California Institute of Technology and *Rockwell International Science Center
10:25 am		Coffee Break
10:45 am	Ma4	"Scanning Tunneling Microscope-Based Nanolithography: Nanometer Scale Patterning and Oxidation of Silicon Surfaces (invited)" J.W. Lyding University of Illinois
	Ma5	"STM/AFM Based Fabrication of Semiconductor Nanostructures" P.M. Campbell, E.S. Snow, P.J. McMarr Naval Research Laboratory
11:55 am	Ma6	"High Speed Optical and Electronic Probes with High Spatial Resolution" T.B. Norris, S. Smith and J. Nees University of Michigan S. Williamson Picometrix, Inc.
12:30 pm		Lunch
2:00 pm		Discussion Session/*ad hoc* Meetings/Free Time
6:00 pm		Dinner
7:00 pm	Mp1	"Quantum Transport in Mesoscopic Devices with Structural Imperfections and in Mesoscopic Tunneling Arrays" (invited) D.Z.-Y. Ting, S.K. Kirby and T.C. McGill California Institute of Technology
7:40 pm	Mp2	"The Effects of Structural Disorder in Planar Nanostructures" D. Jovanovic, J.P. Leburton, H. Chang, R. Grundbacher and I. Adesida University of Illinois

Monday, April 25, 1994 (continued)

8:10 pm	Mp3	"Dissipative Electron Transport over Quarter-Wavelength and Half-Wavelength Periodic Heterostructures" L.F. Register, K. Hess, F. Capasso* and C. Sirtori University of Illinois and *A.T.&T. Bell Laboratories
8:40 pm	Mp4	"Interface Roughness, Phonon Scattering, and The Valley Current of a Double Quantum Well Structure" R. Lake, J. Luscombe and J. Randall Texas Instruments, Inc.
9:10 pm	Mp5	"Memory Effects in Quantum Transport Theory of Confined Electronic Systems" R. Bertoncini and N. Mauser CRS4 Sardinia
9:40 pm		Discussion Session/Social Hour (cash bar)

Tuesday, April 26, 1994

7:00 am		Breakfast Buffet
8:30 am		SESSION II - Chair: Karl Hess, University of Illinois
8:30 am	Tua1	"Interfacial and Leakage Effects in Quantum Transport Properties of Mesoscopic Devices" (invited) J.R. Barker, A. Asenov and J. Cluckie University of Glasgow
9:10 am	Tua2	"Impurity and Surface Roughness Scattering in Quantum Wires" L. Rota University of Oxford S.M. Goodnick Oregon State University
9:40 am	Tua3	"Analytical Calculation of the Conductivity in Low-Dimensional Systems Using Real-Time Green's Functions Formalism" D. Vasileska-Kafedziska, P. Bordone and D.K. Ferry Arizona State University
10:10 am		Coffee Break
10:30 am	Tua4	"Correlation Field Analysis in Split-Gated Narrow Wires" Y. Ochia, K. Yamamoto Chiba University K. Ishibashi, J.P. Bird, Y. Aoyagi, T. Sugano Institute of Physical and Chemical Research D.K. Ferry Arizona State University
11:00 am	Tua5	"Quantized Conductance in an InAs/A1Sb Split-Gate Ballistic Constriction with a 1.0 μm Channel Length" S.J. Koester, C.R. Bolognesi, E.L. Hu and H. Kroener U.C. Santa Barbara M.J. Rooks Cornell University
11:30 am	Tua6	"Well Defined Quantum Wire Fabrication of GaAs by Crystallographic Selective Atomic Layer Epitaxy and the Optical Properties" T. Aoyagi, H. Issiki, S. Iwai, T. Meguro and T. Sugano Institute of Physical and Chemical Research
12:00 Noon		Lunch
2:00 pm		Discussion Session/*ad hoc* Sessions/Free time
6:00 pm		Dinner
7:00 pm	Tup1	"Phonons, Electrons, and their Interactions in Semiconductor Quantum Wires" (invited) T.L. Reinecke Naval Research Lab

Tuesday, April 26, 1994 (continued)

7:40 pm	Tup2	"Confined and Interface Phonons and their Interactions with Carriers as Modified by Surfaces and Interfaces in Mesoscopic (invited)" Structures M.A. Stroscio, G.J. Iafrate Army Research Office K.W. Kim and M.A. Littlejohn North Carolina State University H.L. Grubin SRA, Inc.
8:20 pm	Tup3	"Acoustic Phonon Relaxation Rates in Valence Band Quantum Wells" G. Edwards, E.C. Valadares and F.W. Sheard University of Nottingham
8:50 pm	Tup4	"Number and Current Fluctuations as a Probe for Contact Modeling of Ballistic One-Dimensional Structures" T. Kuhn University of Stuttgart L. Reggiani University of Modena L. Varani University of Science and Technology of Languedoc
9:20 pm		Discussion Session/Social Hour (cash bar)

Wednesday, April 27, 1994

7:00 am		Breakfast Buffet
8:30 am		SESSION III - Chair: Tom McGill, Cal Tech
8:30 am	Wa1	"High Resolution Microscopy of Interfaces in Thin Film Heterostructures" (invited) Z. Liliental-Weber Lawrence Berkeley Laboratory
9:10 am	Wa2	"Hydrogen Passivation of Near-Surface GaAs/A1GaAs Unstrained Quantum Wells" Y.-L. Chang, I.-H. Tan, W. Wilddra, S.I. Yi, J. Merz, E. Hu and H. Weinberg UC Santa Barbara
9:40 am	Wa3	"Photoluminescence Characterization of Sidewall Surfaces in Dry-Etched InGaAs/InP Quantum Wires and Dots" S. Q. Gu, E. Reuter, Q. Xu, H. Chang, R. Panepucci, I. Adesida, S.G. Bishop University of Illinois C. Caneau and R. Bhat Bell Communications Research
10:10 am		Coffee Break
10:30 am	Wa4	"Structures and Properties of Self-Assembled InGaAs Quantum Dots" S. Fafard, D. Leonard, G. Wang, Y.H. Zhang, J.E. Bowers, J.L. Merz and P. Petroff UC Santa Barbara
11:00 am	Wa5	"Si-Interlayer Based Interface Control Technology for Compound Semiconductor Mesoscopic Structures" H. Hasegawa, S. Kodama, S. Kasai, K. Sasaki and H. Fujikura Hokkaido University
11:30 am	Wa6	"Air-Bridges and Sub-Micron Gating: A Key Fabrication Technology for Mesoscopic Devices" M.E. Sherwin, J.A. Simmons, J.F. Klem and R. Corless Sandia National Laboratories
12:00 Noon		Lunch
2:00 pm		Discussion Session/*ad hoc* sessions/free time
6:00 pm		Dinner
7:00 pm	Wp1	"Low-Dimensional Resonant Tunneling and Coulomb Blockade: A Comparison of Fabricated versus Impurity Confinement" M.A. Reed, M.R. Deshande, E.S. Hornbeck and N. Dekker Yale University
7:30 pm	Wp2	"Resonant Magnetotunnelling Spectroscopy of InAs/GaSb/A1Sb Interband Tunnelling Diodes" R.R. Marquardt, D.A. Collins, Y. X. Liu, D.Z.-Y. Ting and T.C. McGill California Institute of Technology

Wednesday, April 27, 1994 (continued)

8:00 pm	Wp3	"Equilibrium and Nonequilibrium Charge Distributions at Semiconductor - Semiconductor and Semiconductor-Metal Heterointerfaces via the Quantum Liouville Equation" H.L. Grubin, T.R. Govindan Scientific Research Associates, Inc. D.K. Ferry Arizona State University
8:30 pm	Wp4	"One-Dimensional Strong Correlation Effects on Nanometer-Size Quantum Wire Device Performance" S. Das Sarma University of Maryland
9:00 pm	Wp5	"Persistent Currents in Finite-Width Mesoscopic Multi-Channel Rings" L. Wendler and V.M. Fomi Martin-Luther-University Halle
9:30 pm		Discussion Session/Social hour (cash bar)

Thursday, April 28, 1994

7:00 am		Breakfast Buffet
8:30 am		SESSION IV - Chair, Mark Reed, Yale University
8:30 am	Tha1	"Capacitance and Electronic Structure of Quantum Dots (invited)" M. Macucci University of Pisa
9:10 am	Tha2	"Non-Equilibrium Transport in Lateral Double Constriction Devices" C. Berven, M.N. Wybourne University of Oregon S.M. Goodnick, N. Harff Oregon State University D.D. Smith Army Research Laboratory
9:40 am	Tha3	"Numerical Simulation of Electron Confinement in Quantum Dot Structures" M. Chen and W. Porod University of Notre Dame
10:10 am		Coffee Break
10:30 am	Tha4	"High Bias Transport through Quantum Dots" G. Klimeck, R.K. Lake, S. Dutta Purdue University G.W. Bryant Army Research Laboratory
11:00 am	Tha5	"Interface Binding and Quantum Dot Self-Consistent Electronic Structure" M. Stopa, Y. Aoyagi and T. Sugano Institute for Physical and Chemical Research
11:30 am	Tha6	"Electrical Transport in the Quantum Dot in the Edge State Regime" K. Ishibashi, J.P. Bird, M. Stopa, J.P. Barnes, T. Sugano and Y. Aoyagi Institute for Physical and Chemical Research
12:00 Noon	Tha7	"Time Constant for an Atomic Relay Computed by *ab initio* Molecular Dynamics" P. von Allmen and K. Hess University of Illinois
12:30 pm		Lunch
2:00 pm		Discussion Session/*ad hoc* sessions/free time
6:00 pm		Banquet

Friday, April 29, 1994

7:00 am		Breakfast Buffet
8:30 am		SESSION V - Chair: Larry Cooper, ONR
8:30 am	Fa1	"Quantum Cellular Automata" (invited) C.S. Lent University of Notre Dame
9:10 am	Fa2	"Chemical Patterns as Building Blocks for Mesoscopic Structures" J. Pearson, G. Doolen, and B. Hasslacher Los Alamos National Laboratory
9:40 am	Fa3	"Buried Structure for Coupled Electron Waveguides" F. Wakaya, A. Nozawa, J. Yanagisaw, Y. Yuba, S. Takaoka, K. Murase and K. Gamo Osaka University
10:10 am		Coffee Break
10:30 am	Fa4	"Direct Patterning of SiO_2 by Carbon-Enhanced Vapor Etching" J.M. Ryan, J. Allgaier, M.N. Kozicki and D.K. Ferry Arizona State University
11:00 am	Fa5	"Tunneling and Anti-Crossing in Double Quantum Well Heterostructures with In-Plane Magnetic" J.A. Simmons, S.K. Lyo, J.F. Klem, M.E. Sherwin and N. Harff Sandia National Laboratory
11:30 am	Fa6	"Interference in the Nonlocal Shubnikov-de Haas Effect in a GaAs/A1GaAs 2DEG" N.F. Deutscher, J.M. Ryan and D.K. Ferry Arizona State University
12:00 Noon		Lunch and Adjournment

SURFACES AND INTERFACES IN MESOSCOPIC DEVICES

ABSTRACTS

April 24-29, 1993
Keauhou Beach Hotel
Kona, Hawaii

ENGINEERING FOUNDATION

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SURFACES AND INTERFACES IN MESOSCOPIC DEVICES
Kona, Hawaii, April 24-29, 1993

ABSTRACTS

Monday, April 25

Ma1 (Invited) Cross-Sectional Scanning Tunneling Microscopy of Semiconductor Structures, Randall M. Feenstra, *IBM T. J. Watson Research Center.* Cross-sectional scanning tunneling microscopy (STM) and spectroscopy are used to study semi-conductor superlattices. The structures are cleaved in ultra-high-vacuum, and measurements are performed on the edge of the grown layers. Low-temperature-grown GaAs, containing about 1 atomic % excess arsenic, has been studied. In unannealed material the excess arsenic is seen as point defects (antisites), and in annealed material arsenic precipitates are found. Spectroscopic measurements are used to determine the midgap states induced by these structural defects. Effects of on-site and off-site Coulomb interactions are apparent in the spectra. Studies of other types of epitaxial structures, including InAs/GaSb super-lattices, will also be described.

Ma2 Interfacial Properties of InAs/$Ga_{1-x}In_xSb$ Superlattices Studied by Cross-Sectional Scanning Tunneling Microscopy, E.T. Yu and A.Y. Lew, *Dept. of Electrical and Computer Engineering, University of California, San Diego, LaJolla, CA 92093-0407,* D.H. Chow and R.H. Miles, *Hughes Research Laboratories, Malibu, CA 90265.* Cross-sectional scanning tunneling microscopy (STM) is a powerful tool for the investigation of nanometer-scale structural and electronic properties of semiconductor hetero-structures. We have used cross-sectional STM imaging and spectroscopy to study III-V heterostructures grown by molecular-beam epitaxy. Tunneling experiments were conducted in an ultra-high vacuum chamber with a base pressure of approximately 3×10^{-10} Torr. Samples were cleaved *in situ* , yielding atomically flat, unpinned (110) cross-sectional surfaces on which the tunneling measurements were performed. The atomic-scale morphology and electronic structure of epitaxial layers and hetero-junction interfaces can be probed directly in the cross-sectional geometry.
Constant-current imaging and current-voltage spectroscopy have been used to investigate the structural and electronic properties of InAs/$Ga_{1-x}In_xSb$ strained-layer superlattices grown on GaSb substrates. These materials are of interest for infrared imaging applications. Interfacial properties are of particular importance in these structures: because both the Group III and Group V constituents change across each interface in the superlattice, two distinct composi-tions—GaInAs-like and InSb-like—are possible even for structurally perfect interfaces. Band-structure calculations and energy-gap measurements suggest that details of interface composition and the resulting electronic structure could exert a significant influence on device performance. Shown here is a 150Åx150Å constant-current image obtained at negative sample bias of a superlattice consisting of 33Å InAs alternating with 25Å $Ga_{0.75}In_{0.25}Sb$. Atomic resolution has been attained, and contrast is observed between the InAs and $Ga_{0.75}In_{0.25}Sb$ layers. This contrast is electronically induced, rather than corresponding to actual topographic features on the cross-sectional surface. Spectroscopic measurements performed while tunneling into the superlattice layers appear to be quite strongly influenced by extended superlattice states, rather than corresponding exclusively to the bulk-like band structure of the individual constituent materials.

Ma3 RHEED and XPS Studies of Interfaces and Surfaces in the Mixed Anion InAs/GaSb/AlSb Material System, M.W. Wang, D.A. Collins, and T.C. McGill, *T.J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology 128-95, Pasadena, CA 91125;* and R.W. Grant, *Rockwell International Science Center, Thousand Oaks, CA 91360.* The mixed anion InAs/GaSb/AlSb material system is a promising candidate for realizing useful versions of many meso-scopic structures. Among its beneficial properties are flexibility in choosing band alignments, small InAs and GaSb effective masses which increase quantum effect length scales, and a negative Schottky barrier for n-InAs which facilitates ohmic contacting. In addition, the unique staggered band alignment of InAs/GaSb, which has resulted in a large number of novel devices, may also help to solve the problems of doping extremely small devices since charge transfer occurs naturally between these two materials. In order to realize the promise of this material system, some basic issues inherent to mixed anion systems must first be resolved. These include controlling the interface bond type and abruptness, and reducing levels of anion cross incorporation. We will present RHEED and XPS studies of InAs/GaSb and InAs/GaInSb interfaces. The abruptness of the interface will be discussed as a function of interface

bond type, whether cracked or uncracked anion fluxes are employed and the type and extent of anion interrupt employed at the heterointerface. The effect of anion interrupts will be discussed including chemical and structural studies of InAs surfaces exposed to Sb_x fluxes and GaSb surfaces exposed to As_x fluxes. XPS and RHEED studies of Sb diffusion into InAs layers grown on both GaSb or GaInSb will also be discussed.

Ma4 (Invited) Scanning Tunneling Microscope-Based Nanolithography: Nanometer Scale Patterning and Oxidation of Silicon Surfaces+, Joseph W. Lyding, *ECE Department and Beckman Institute, University of Illinois at Urbana-Champaign.* Nanometer scale patterning of hydrogen terminated Si(100) surfaces has been achieved by using an ultrahigh vacuum (UHV) scanning tunneling microscope (STM) to selectively remove the hydrogen passivation layer. By preparing and hydrogen passivating the Si(100) 2xl surface in UHV it is possible to avoid the contamination issues associated with traditional wet chemical processing methods. Hydrogen passivation on silicon represents the simplest possible resist system for nanolithography experiments. The monohydride H-Si(100) 2xl surface is readily prepared in UHV, presenting a structurally and chemically uniform surface for subsequent patterning. By operating the STM in field emission, the hydrogen passivation is selectively removed leaving behine atomically clean silicon. The depassivation mechanism is well understood and occurs when the classical kinetic energy of the STM electrons exceeds the bond strength. Furthermore, atomic hydrogen recombines and evolves as H_2, preventing repassivation of previously patterned areas of the surface. Using this technique we demonstrate patterning resolntion down to < 1 nm, i.e., it is possible to selectively depassivate individual Si(100) 2xl atomic dimer rows. A variety of patterns will be shown that demonstrate a wide range of fiela emission conditions and detailed nature of the tunneling probe structure. After STM patterning, the dangling bond returns to the silicon surface atoms, suggesting many interesting possibilities for selective surface chemistry. We have explored this possibility by selectively oxidizing the patterned areas. The surrounding H-passivated regions are unaffected by oxygen exposure, indicating no degradation of patterning resoluhon. Progress in applying these techniques to the nanofabrication of mesoscopic device structures will also be presented.

+ Supported by the Office of Naval Research URI under contract N00014-J-1519

Ma5 STM/AFM-Based Fabrication of Semiconductor Nanostructures, P.M. Campbell, E.S. Snow, and P.J. McMarr, *Naval Research Laboratory, Wash. DC 20375-5000.* We recently reported the fabrication of silicon nanostructures through the selective oxidation, induced by the highly local electric field of an STM tip operated in air, of an H-passivated (100) Si surface[1]. This thin surface oxide acts as a mask against deep (up to 300 nm) liquid etching of the unoxidized regions of the silicon. Continuous wires of width 20 nm and isolated dots of diameter 10 nm have been fabricated. More complex patterns can be written by pulsing the STM bias pixel-by-pixel to a suitable writing voltage during a low-bias (hence non-exposing) scan. In a variation of this technique, we use a metal-coated AFM tip, for which the exposing bias is inde-pendent of the force-controlled feedback. The exposed pattern can thus be repeatedly imaged without risk of further exposure. With the STM, such latent images must be taken with care. The write speed is fast (typically 10 μm/s for the STM, and up to 1 mm/s for the AFM). Large, complex patterns can thus be written in a matter of seconds. We have also applied this technique to III-V semiconductors (which lack a stable passivation and a suitable oxide) by growing a 5 nm surface layer of epitaxial Si. Upon patterning as above, this Si layer serves as an etch mask for the III-V below[2]. Narrow conducting silicon wires between contact pads but electrically isolated from the substrate were fabricated with this process on SIMOX (a silicon layer on top of a buried insulating layer of SiO_2 formed by oxygen implantation and annealing). Backgating drives these wires into accumulation or inversion, thus allowing independent control of the conductance and carrier type of the wires[3]. These wires have interesting physical properties and also form the basic build-ing blocks for more complex devices (such as nanometer-scale side-gated FETs and single-electron transistors) which are of direct interest to our long-term agenda. Such devices will be very sensitive at the atomic level to the nature of the semiconductor/oxide and semiconductor/ambient interfaces, which will in turn depend on atomic level control of the surface processing. Of particular interest will be the role of individual charge traps at these interfaces. Earlier work by us showed that the transport and optical properties of suitably-constricted small structures can be dominated by the charge state of a single trap if it is located in a critical region[4]. Our goal is the atomic control of the surface and interface properties of these lateral nanostructures for the creation of new classes of optoelectronic devices whose operating principles are based on the mediation

of current flow through small regions by the action of such critically-situated single charges. Our approach offers several advantages over conventional nanofabrication techniques. The modified surface layer is a near-monolayer resist, which should allow near-atomic scale patterning. Because only the top few monolayers are modified, the bulk properties underneath are not damaged. There are no proximity effects from backscattered beams, hence very densely packed patterns can be fabricated. Pattern registration is trivially easy because the same tip can be used either to image or to expose. While metal liftoff is not practical with this technique, we have patterned the self-assembled monolayer n-octadecyltrichlorosilane (OTS), which can be used to nucleate selective metal deposition. The full realization of these techniques will make the fabrication of nanometer-scale devices accessible through simple, easy, reliable processes using relatively inexpensive and widely available equipment. The demonstrated ability of the STM to manipulate and position single atoms on a surface suggests that STM/AFM-based patterning may surpass e-beam lithography in defining the ultimate size limit for pattern generation.

[1] E.S. Snow, P.M. Campbell, and P.J. McMarr, Appl. Phys. Lett. **63**, 749 (1993).

[2] E.S. Snow, P.M. Campbell, and B.V. Shanabrook, to be published in 12/27/93 issue of Appl. Phys. Lett.

[3] P.M. Campbell, E.S. Snow, and P.J. McMarr, 6th Int. Conf. on Modulated Semiconductor Structures, Garmisch-Partenkirchen, Germany, 23-27 August 1993; to be published in Solid State Electronics.

[4] P.M. Campbell et al., Phys.Rev. Lett. **67**, 1330 (1991); also, E.S. Snow, P.M. Campbell, and D.S. Katzer, Phys. Rev. B15 (Rapid Com.) **47**, 16032 (1993).

Ma6 High Speed Optical and Electronic Probes with High Spatial Resolution, T.B. Norris, S. Smith, and J. Nees, *Center for Ultrafast Optical Science, Univ. of Michigan, 2200 Bonisteel Blvd., Ann Arbor, MI 48109-2099,* and S. Williamson, *Picometrix, Inc., P.O. Box 130245, Ann Arbor, MI. 48113.* In order to probe the dynamics of carriers in mesoscale electronic and optical structures, it will ultimately be necessary to access single devices. There are a number of ultrafast optical techniques which we have used in recent years for the investigation of high speed processes in bulk semiconductor material or in device structures. These include time-resolved luminescence and absorption spectroscopy for measure-ment of carrier relaxation and transport in bulk and quantum-well structures, and electro-optic and photoconductive sampling of the response of devices to transient electric fields. Ultrafast optical techniques have enabled the direct investigation of transport up to frequencies exceeding 1 THz, or down to the sub-100-fs time scale. However, because the wavelength of light is much larger than the size of mesoscopic (50-nm-scale) structures, conventional optical or optoelectronic probes cannot in general be used for their investigation. In the past few years, there has been a series of remarkable advances in the field of scanning microscopy, including scanning tunneling microscopy (STM), atomic-force microscopy (AFM), and near-field scanning optical microscopy (NSOM). These techniques afford spatial resolution ranging from the order of 50 nm (with NSOM) down to a few nm (with STM). Our goal is to couple the techniques of ultrafast optics with scanning microscopy to enable extremely high spatial and temporal resolution to be obtained simultaneously. In this paper, we will describe two approaches under development in our laboratory. First, we are developing a near-field scanning optical probe using ultrashort optical pulses from a Ti:sapphire laser, suitable for investigation of mesoscopic III-V semi-conductor structures. We have demonstrated the measurement of 100-fs pulses through an NSOM probe, and a spatial resolution of below 100 nm. Applications of this probe to investigations of semiconductor structures are in progress. We have also demonstrated a photoconductive sampling probe which has single-picosecond response for the investigation of the dynamics of ultra-small electronic devices and circuits. This probe has been demonstrated to have microvolt sensitivity, and its invasiveness to the circuit under test can be kept very low. The probe has submicron spatial resolution capability. We are currently coupling this probe to an AFM to allow imaging and position-ing of the probe on ultrafine circuits. In this paper we will review the state of the art in combined high spatial and temporal resolution probes, and discuss the potential of these probes for the investigation of mesoscopic systems.

Mp1 (Invited) Quantum Transport in Meso-scopic Devices with Structural Imperfections and in Mesoscopic Tunneling Arrays, D. Z.-Y. Ting, S.K. Kirby, and T.C. McGill, *Thomas J. Watson, Sr. Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA 91125.* Quantum transport in mesoscopic devices is examined with an exactly solvable real-space three-dimensional supercell model. The flexibility of our model has enabled us to include the effects due to impurities, interface roughness, and alloy disorder in our studies of 2D (double barrier heterostructure), 1D (quantum wires electron waveguides), and 0D (quantum dots) mesoscopic device structures. Our studies reveal that structural

imperfec-tions can not only produce additional scattering processes in a perturbative sense, under the right circumstances, they can also substantially alter the quantized electronic states, leading to modified transport properties. For example, we have demonstrated that interfacial inhomogeneities in double barrier resonant tunneling diodes can induce lateral localization of wave functions; strongly attractive impurities can produce additional transmission resonances; and surface roughness in quantum dots can cause large fluctuations in transmission characteristics. In addition, we will also discuss the application of our method to quantum transport in arrays of mesoscopic devices.

Mp2 The Effects of Structural Disorder in Planar Nanostructures, D. Jovanovic, J.P. Leburton, H. Chang, R. Grundbacher and I. Adesida, *Dept. of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801.* Inherent processing anomalies, such as surface and interface roughness, have a profound influence on transport characteristics as device dimensions shrink below critical screening lengths. As an example, we present experimental data on a fabricated thin-gated quantum wire device which exhibits near-threshold resonant tunneling character-istics. The rarity and inconsistency of the resonant phenomenon over the device population suggests that the effect is controlled by random geometrical factors. To better assess the potential role of structural disorder, we have performed 3D self-consistent Schrödinger-Poisson simulations of the experimental device geometry and evaluated its transport characteristics. Our model includes all quantized regions and relies on the adiabatic quasi-1D eigenenergy to evaluate the finite temperature current. Simulations in the virtual crystal approximation reveal no resonant behavior in the near-threshold regime. However, the inclusion of realistic interface and surface roughness in the simulation results in I-V characteristics that exhibit varying degrees of resonant behavior near the onset of conduction and strongly resemble the experimental data. The appearance of resonant-tunneling features depends on the relative magnitude of the tunneling and thermionic emission components of the current. The weak localization induced by disorder allows enhanced penetration through barrier regions thereby enhancing resonant tunneling with respect to thermionic emission. Our model suggests that structural disorder has a significant impact on the transport properties of planar devices and that the intentional alteration of interfaces may lead to more robust quantum transport effects.

Mp3 Dissipative Electron Transport Over Quarter-Wavelength and Half-Wavelength Periodic Hetero-structures, L.F. Register and K. Hess, *Beckman Inst., University of Illinois at Urbana-Champaign, Urbana, Ill. 61801,* and F. Capasso and C. Sirtori, *AT&T Bell Labs., Murray Hill, NJ 07974.* The effects of dissipative polar-optical-phonon scattering on electron transport over periodic heterostructures is numerically simulated. The numerical method used is based on the time-dependent Schrödinger equation. Multi-dimensionality, an arbitrarily variable potential energy function and open boundary conditions allow simulation of transient through steady-state electron transport in mesoscopic structures under far-from-equilibrium conditions. The inclusion of a limited number of harmonic oscillator coordinates in addition to the electron coordinates allows simultaneous simulation of dissipative coupling. Coupling between the electron and oscillator coordinates is via Monte Carlo sampled potential functions that are obtained from the true electron-phonon coupling potentials and is exact to first order. Here, in particular, the effects of polar-optical scattering on resonant reflection from quarter-wavelength periodic hetero-structures and transmission over half-wavelength periodic heterostructures is simulated. The coupling between resonant and off-resonant electron states can be expected to alter both the electron transmission probabilities and the nominal phonon emission rates.

Mp4 Interface Roughness, Phonon Scattering, and the Valley Current of a Double Quantum Well Structure, Roger Lake, James Luscombe and John Randall, *Central Research Laboratories, Texas Instruments, Inc., Dallas, TX.* Interfaces on a nanometer scale create the quantum and charge confinement that provide the physical basis for all nanoelectronic device proposals. The approach which appears most practical for creating a room temperature nano-electronic semiconductor technology is based on resonant tunneling. If resonant tunneling devices are to be the basis of a nanometer ULSI technology, the off-state (off-resonant) current must be strongly suppressed. One approach to solving this problem is to fabricate two or more resonant tunneling structures in series. Numerical simulations of a double quantum well structure based on the single-particle Schrödinger equation which ignore scattering predict the usual many-order-of-magnitude suppression of the off-resonant current. We have performed analytical calculations which include optical phonon scattering that predict an enhancement of the valley current by a factor of ~ 1000 for typical device parameters. Both analytical and numerical analyses of a double-well structure using the non-equilibrium Green function approach will be presented. Particular attention will be given to the role of optical phonon and interface-roughness scattering in determining the magnitude of the valley

current. Comparisons with experimental data, which show some surprising features, will be made.

Mp5 Memory Effects in Quantum Transport Theory of Confined Electronic Systems, R. Bertoncini and N. Mausert, *CRS4, Casella Postale 488, I-09123 Cagliari, Italy.* Quantum behavior may manifest itself not only over the spatial scales on which coherence is maintained, but also through the time scales on which the transport processes occur. In particular, the study of mesoscopic systems requires specific length and time coarse-graining procedures which yield the correct separation between "fast" and "slow" (mesoscopic) variables that is required in order to address the dynamical processes whereby quantum correlations are diminished or destroyed, and to ascertain the way macroscopic transport quantities are influenced by both quantum inter-ference and quantization of the electronic states. With this in mind, we investigate how level quantization modifies the nonMarkovian behavior of confined electron systems, and how this affects the way scattering mechanisms operate in a mesoscopic solid-state device. We show how the effects of geometrical confinement can be analyzed by the Generalized Langevin Equation (GLE) and memory-function techniques. This is a macroscopic approach which, while incorporating causality, is sufficiently general to treat the case of confined electron gases with both elastic and inelastic dissipation mechanisms. The particular structure of the GLE, where dissipative and random, fluctuating forces are separated, enable us to individuate the different time scales on which the transport regimes dominated by lateral confinement and those dominated by dephasing scattering mechanisms, manifest themselves. Our method leads to the appearance of a "ballistic" memory function which demonstrates how confinement effects can be associated with retardation in the system, by increasing the memory term efficiency in the GLE. More importantly, a renormalized true-force correlation function shows how geometrical confinement also modifies the nonMarkovian behavior caused by the interaction with the crystal environ-ment. For instance, dissipation mechanisms such as scattering by elastic impurities retain their phase-breaking properties at times longer than in 3D systems. In our formulation, no assump-tion about the nature of the boundaries is made. By taking into account the different time scales on which the ballistic and interaction true-force correlation functions operate, and how they compare with the frequency ranges relevant to the corresponding random-force correlations, we show that the phenomenon described above is a general consequence of the interaction between lateral quantization and scatter-ing potentials: On the one hand, the "granularity" caused by the laterally imposed confinement reduces the system phase-space and acts towards suppressing the scattering processes. On the other hand, the very same confining potential acts as a diffusive scattering mechanism which correlates with the other scattering centers in the crystal, causing transitions and, therefore, phase randomization, between the nonpropa-gating transverse modes in the structure. Finally, an expression for the electrical conductivity valid at finite temperatures and at all frequencies, and satisfying the appropriate limits, be given.

Tuesday, April 26

Tua1 (Invited) Interfacial and Leakage Effects in the Quantum Transport Properties of Mesoscopic Devices, J.R. Barker, A. Asenov and J. Cluckie, *Nanoelectronics Research Centre, Dept. of Electronic and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, UK.* The development of a wide range of exploratory ultra-small semiconductor devices with feature sizes of the order of 30 nm and smaller has focused attention on the importance of the interfaces, boundaries and environment of the device on the transport, switching and capacitative properties of a device. In the present paper we focus on the implications of a small, fluctuating number of strongly-interacting carriers present within the volume of a conventional channel device (FET or quantum point contact structure) or in the charge confinement region of a single-electronic device (quantum dot, Schottky dot, quantum point contact structure). The effective electrical boundaries of a mesoscopic device are morphologically different from the material boundaries because of screening effects, the fluctuation potential and the existence of leakage paths and remote electrical sources such as the charging-discharging of interface states, traps and impurities. In the case of single electronic devices fabricated from arrays of metallized Schottky dots on a semi-conductor substrate our detailed 3D numerical simulations suggest that it is possible to exert considerable control over the electrostatic profile and the subsequent stability of correlated single electron switching by a combination of screening islands and substrate engineer-ing to suppress the larger image charge fluctuations. These calculations are based on the grainy version of Poisson's equation in which the source charge density derives from discrete and continuous charge distributions. In small confining volumes the carrier distribution is highly correlated due to the Coulomb interaction, Coulomb blockade effects and the ordering induced by spatial quantization. In recent reports we have discussed the phenomenon of Coulomb assisted resonant tunneling a quasi-1D effect in which one electron may tunnel

through a confining barrier via the resonant state formed by the barrier and a second carrier. This process is expected to be significant in some classes of mesoscopic device and will provide a serious leakage mechanism. Analytical and numerical models of this effect are presented. The internal states of a confining volume including special resonances may be strongly influenced by static and transient fluctuations in the device environment. Such effects become evident via level shifts (perturbation affecting the real part of the self-energy) and lifetimes (imaginary part of the self-energy, including leakage processes) due to interaction with the environment. Since these perturbations include the influence of discrete carriers incident on the injection regions of the device there will be a significant influence on the shot noise statistics of the extracted current. These processes must be understood if it is intended to achieve for limiting scale digital electronics what has already been achieved in quantum-limit digital opto-electronic communication systems.

Tua2 Impurity and Surface Roughness Scattering in Quantum Wires: Is the Game Really Worth It?, Lucio Rota, *Clarendon Laboratory, Dept. of Physics, University of Oxford, Parks, Road, Oxford OX1 3PU, UK.* and Stephen M. Goodnick, *Dept. of Electrical and Computer Engineering, Oregon State University, Corvallis, OR 97331.* In the last few years the interest in transport in mesoscopic and low dimensional systems has rapidly increased. Due to the singular one-dimensional density of states, it has been predicted that optical and electronic devices based on quantum wires should be able to achieve improved performance. It was initially thought that in quantum wells and wires the efficiency of the electron-phonon interaction should have been reduced due to the electron and phonon confine-ment. However, after several years of debate, it is now widely accepted that the total effect of confined and interface phonon modes is more or less the same as bulk phonons. However, the nature of defect scattering is quite different as the dimensionality of the system is reduced. Quantum wires have been fabricated using a variety of techniques, most of which require some kind of etching procedure and induce defects inside the wire as well as surface roughness at the interfaces. In this work we investigate the effect on nonequilibrium transport of impurity and surface roughness scattering in a multi-subband quantum wires with rectangular cross section through an ensemble Monte Carlo simulation. The model contains the usual interactions associated with inter- and intrasubband bulk and confined polar optical phonons, as well as carrier-carrier scattering as discussed elsewhere[1]. Within this model, surface roughness scattering due to the sidewalls and the AlGaAs/GaAs interface is added, as well as remote and bulk ionized impurity scattering. Due to the double confinement in a side-etched quantum wire, the intersubband form factors are usually small so that intra-subband scattering is the more relevant interaction. For an elastic process in a quantum wire, this means that the only relevant final state available is that with opposite direction of the wave vector, which results in a strong reduction of the drift velocity for both impurity and surface roughness scattering. We have studied different configurations for the interface roughness, and are able to vary the rms height of roughness as well as the lateral distribution of defects. Our study shows that in real quantum wires, very high quality interfaces are needed in order to achieve a significant improvement in the transport properties compared to 3D systems.

[1] L. Rota et al., Phys. Rev. B **47**, 1632 (1993).

Tua3 Analytical Calculation of the Conductivity in Low-Dimensional Systems Using Real-Time Green's Functions Formalism*, Dragica Vasileska-Kafedziska, Paolo Bordone** and David K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-6206.* The aim of this communication is to present an analytical derivation for the nonequilibrium conductivity in low-dimensional systems. Under these conditions, surface-roughness and impurity scattering dominate the transport properties of the system. Surface-roughness scattering is treated like random potential scattering with Gaussian correlation function[1]. To avoid mathematical complications which are of no physical interest, we assume that the electrons are scattered by randomly located but identical δ-function impurity potentials with strength u. Since we are interested in transport properties of the system, we use the real-time Green's functions formalism which is the most general approach for the analysis of nonequilibrium phenomena. Comparison with zero-temperature derivation will also be presented.

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[1] R.E. Prange, T. Nee, Phys. Rev. **168**, No. 3, 779 (1968).

Tua4 Correlation Field Analysis in Split-Gated Narrow Wires, Y. Ochiai, K. Yamamoto, *Dept. of Materials Science, Chiba University, 1-33 Yayoi, Inage, Chiba 263, Japan;* K. Ishibashi, J.P. Bird, Y. Aoyagi, T. Sugano, *Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama 351-01, Japan;* and D.K. Ferry, *Dept. of Electrical Engineering, Arizona State University, Tempe,*

Arizona, 85287-5706. We are studying quantum interference effects in narrow GaAs/A1GaAs wires of quasi-ballistic regime, where the wire dimensions are comparable to or less than the phase coherence length of electron transport. It is well known that the low temperature magnetoresistance (MR) of a narrow wire shows universal conduction fluctuations (UCF), which are demonstrated in the theoretical study of Lee and Stone. At lower magnetic fields, the Lee-Stone correlation field, B_C, gives a measure of the field scale of the fluctuations. On the other hand, at higher fields ($\omega_c\tau>1$), , Landau quantization becomes dominant and the Lee-Stone treatment, based on perturbation, is difficult to apply to those systems. As the field increases, suppression of interference effects has been observed and the B_c shifts to a higher field. It seems that the effective area for the interference channels is reduced by the high magnetic field. In order to search near future applications based on "mesoscopic" devices, we have studied the UCF observed in the low-temperature MR of quasi-ballistic, split gated GaAs/A1GaAs wires. Since the width of the wires can be easily varied by controlling the negative gate voltage, we have obtained the wire-width and the magnetic field dependences of the correlation field B_c by analyzing auto-correlation function of the UCF in the low field MR and observed phase-coherence behaviors of electron waves. Estimating a boundary correlation field defined at $\omega_c\tau=1$, we can discuss a mean free path in diffusive wires. However, in the case of a quasi-ballistic wire of the width, W, such a boundary field, B_o, should be defined by $r_c=W$ instead of above criterion, $\omega_c\tau=1$, and shows a clear change at B_o as the W is varied. Our result of such a boundary field analysis comes from a dynamical property of electron wave propagations near the gates and indicates a possibility of determination of microscopic mean free path of narrow wires.

Tua5 Quantized Conductance in an InAs/A1Sb Split-Gate Ballistic Constriction with 1.0 μm Channel Length, Steven J. Koester, Colombo R. Bolognesi, Evelyn L. Hu, and Herbert Kroemer, *Dept of Electrical and Computer Engineering, University of California at Santa Barbara,* and Michael J. Rooks, *National Nanofabrication Facility, Cornell University, Ithaca, NY 14853.* We report the observation of quantized conductance in InAs/A1Sb split-gate ballistic constrictions with channel lengths as long as 1.0 μm. This is the longest split-gate device fabricated in any material system to display conductance steps at integer multiples of $2e^2/h$, indicating ballistic transport over the entire channel length. A comparison of this characteristic to that of a much shorter constriction located on the same mesa indicates very little degradation in the conductance characteristic from L = 0.20 μm to 1.0 μm. Our data contrast with previous reports on split-gate structures fabricated in GaAs/A1GaAs materials.[1] Those studies indicated severe degradation of the conductance steps with increasing constriction length, where the quantization was essentially unobservable for L≥0.6 μm. We believe the enhanced length characteristics of split gates in InAs/A1Sb compared to GaAs/A1GaAs stem from the ability to increase the energy spacing of the one-dimensional subbands to values greater than the amplitude of potential fluctuations caused by the random donor distribution.[2] This is accomplished much more readily in InAs/A1Sb than GaAs/A1GaAs for two main reasons. 1) For a given device geometry, the 1D subband spacings should be larger in InAs than in GaAs, due to the light effective mass of InAs ($m^*\Gamma=0.023m_o$), which is approximately one-third that of GaAs. 2) In InAs/A1Sb quantum wells, the donors are located at the surface of the GaSb capping layer,[3] and therefore can be kept much farther from the conducting layer than in traditional δ-doped GaAs/A1GaAs 2DEGs. There-fore, the amplitude of potential fluctuations due to impurities should be considerably reduced for InAs-based structures. This work demonstrates that the utility of the InAs/A1Sb material system for the study of electron transport in one-dimensional systems goes beyond its obvious effective mass advantages. The unique surface properties of this material system can be utilized to enhance the transport properties of split-gate devices, and may enable the fundamental transport mechanisms in low-dimensional systems to be more fully explored.

[1] G. Timp, R. Behringer, S. Sampere, J.E. Cunningham, and R.E. Howard, in Nanostructure Physics and Fabrication, edited by M.A. Reed and W.P. Kirk, Academic, Boston, (1989), pp.331-345.
[2] J.A. Nixon, J.H. Davies, and H.U. Baranger, Phys. Rev. B 43, 12638 (1991).
[3] C. Nguyen, B. Brar, H. Kroemer, and J.H. English, Appl. Phys. Lett 60, 1854 (1992).

Tua6 Well Defined Quantum Wire Fabrication of GaAs by Crystallographic Selective Atomic Layer Epitaxy and the Optical Properties, Yoshinobu Aoyagi, Hideo Issiki, Schachi Iwai, Takashi Meguro and Takuo Sugano, *The Institute of Physical and Chemical Research, (RIKEN), Wako-shi, Saitama, 351-01, Japan.* Many efforts on developing techniques for fabricating quantum wire structures have recently been made to realize sophisticated optical and electrical devices with the wire structure. However, the thickness and the interface of the quantum wire

fabricated so far are not well controlled. For example, the thickness of the quantum wire fabricated on the bottom of V-groove or on the top of the triangular corner of the selectively etched substrate crystal, which are well used for examining the optical properties of the quantum wire, is not uniform but the shape is crescent. It is very important to develop the technique to fabricate well-controlled quantum wire structure with uniform thickness and interface for designing new quantum wire devices. Recently we have developed for the first time a new technique for fabricating well-controlled quantum wire structure with atomically uniform thickness and interface by using crystallographic selective atomic layer epitaxy. We have found the crystallo-graphic selective epitaxy is possible for (100) surface and (111) surface of GaAs at a temperature region around 560 C in the atomic layer epitaxy and the selectivity can be controlled by changing the purging time of a source gas of Trimethyl Gallium. By using the characteristics of layer-by-layer and the selective growth of the atomic layer epitaxy, we have succeeded in fabricating the quantum wire structure with a rectangular profile and flat inter-face. This quantum wire embedded in GaAsP is observed to have strong photo-luminescence. This fabrication technique will be a promising technique for fabricating future quantum wire devices. In this conference we report this new fabrication technique of quantum wire with well-controlled inter-face and size, and the optical properties. The future device application of this structure is discussed.

TupI (Invited) Phonons, Electrons and Their Interactions in Semiconductor Quantum Wires, T.L. Reinecke, *Naval Research Laboratory, Washington, D.C. 20375.* The electron and phonon states in quantum wire systems give important information about the structure and quality of these systems, and their interactions describe the basic physics and the role of dimensionality in these structures. In general, the equations for carriers and for phonons in quantum wires are not separable and require numerical solutions in the plane perpendicular to the quantum wires. We have developed efficient one-dimensional integral equation techniques to describe both the electrons and phonons in these systems[1]. Joint theoretical/experimental studies of the optical properties of modulated barrier quantum wires have been made[2] with the Technical Physics Institute of the University of Würzburg. These structures consist of a InGaAs quantum well from which the GaAs overlayer has been selectively etched away. Detailed calculations of the electronic transition energies of these systems have been shown to be in good agreement with the results of photoluminescence and photoluminescence excitation spectro-scopy data for all of the confined quantum wire states for wire widths down to 180A. This agreement indicates that these structures are of high optical quality and have no significant optical "dead layers". In addition, we have shown that magneto-photoluminescence studies of these systems give a new and especially simple way of studying the electronic states of quantum wires[2]. Electron-phonon scattering rates are central to understanding such behavior as quantum wire lasers. Electron relaxation rates involve sums over scattering from all phonons in quantum wires, which consist of confined and interface vibrations. We have given the first rigorous treatment of electron relaxation rates in semiconductor quantum wires such as the GaAs/AlAs system within a macroscopic description of the phonons[3]. This permits us to give results for scattering rates as functions of wire size and shape and to compare quantitatively with bulk-phonon descriptions. We have found that inter-face phonons tend to be localized in the sharp corners of the wire cross sections, and we have shown that scattering rates from the confined phonons are independent of the choice of boundary conditions provided that Maxwell's equations are satisfied. The total scatter-ing rates are found to be fairly insensitive to wire shape as a result of the summation over phonon modes. Interface phonons make significant contributions to the rates for wires of less than ≈ 200 A. For wider wires a bulk phonon description is shown to be appropriate.

[1] P.A. Knipp and T.L. Reinecke, Phys. Rev. B **45**, 9091 (1992); and to be published.

[2] Ch. Gréus, F. Daiminger, A. Forchel, P.A. Knipp, and T.L. Reinecke, Phys. Rev. B **47**, 7626 (1993); and to be published.

[3] P.A. Knipp and T.L. Reinecke, Phys. Rev. B **48**, 5700 (1993); and to be published.

Tup2 (Invited) Confined and Interface Phonons and Their Interactions with Carriers as Modified by Surfaces and Interfaces in Mesoscopic Structures, M.A. Stroscio and G.J. Iafrate, *U.S. Army Research Office, P.O. Box 12211, Research Triangle Park, NC. 27709-2211;* and K.W. Kim and M.A. Littlejohn, *Dept. of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC. 27695-7911.* As device dimensions in nanoscale structures and mesoscopic devices are reduced, the characteristics and interactions of dimensionally-confined phonons deviate substantially from those of bulk semiconductors. This account emphasizes the properties of phonon modes arising in semiconductor quantum wells and quantum wires. In particular, this talk will highlight recent results of both microscopic and macro-scopic models of LO phonons in polar-semiconductor quantum wells and quantum wires as well as elastic continuum models for acoustic phonons in mesoscopic structures with a variety of

cross sectional geometries. Emphasis is placed on dielectric continuum and elastic models of confined and interface phonons. In addition, this talk will provide a brief overview of how the surfaces and interfaces in mesoscopic structures modify the Frohlich, deformation and piezoelectric potentials as a result of phonon confinement.

Tup3 Acoustic Phonon Relaxation Rates in Valence Band Quantum Wells, G. Edwards, E.C. Valadares and F.W. Sheard, *Dept. of Physics, University of Nottingham, NG7 2RD, U.K.* The hole-phonon interaction in semiconductor heterostructure systems plays a fundamental role in determining transport properties and hence also device applications. In a Monte Carlo simulation of a quantum well (QW) based device, knowledge of the hole-phonon scattering rates is an essential input. In contrast to the electron case where the electron-phonon interaction can be treated simply, the hole-phonon interaction in a QW system is very complicated. This is because the hole QW subbands and the hole-phonon interaction require a multiband treatment. The QW interfaces cause strong bulk light hole/heavy hole mixing in the hole subbands and this mixing also strongly affects the hole-phonon interaction. Describing the phonon system also becomes a difficult problem if anisotropy is included. We have set up a general formalism, based on the 6x6 multiband Luttinger Hamiltonian and the corresponding Bir-Pikus deformation potential matrix, for calculating acoustic phonon emission rates in GaAs/AlGaAs valence band QWs[1]. Fermi's Golden rule is employed to calculate the scattering rate[1]. The acoustic phonons are treated as bulk like and in terms of elasticity theory, with anisotropy effects retained rather than the usual isotropic approximation. This formalism extends previous work by incorporating the spin split off band and warping effects and is also capable of treating QWs grown along lower symmetry directions. Thus narrow QWs, where the spin split off band becomes important, can also be tackled by the present method. For symmetric [001] QWs, previous arguments have been generalized to the 6x6 case, to build states with well defined parity associated with the subband Kramers degeneracy[1]. This allows the examination of hole spin relaxation phenomena via acoustic phonon emission, within the framework of the present formalism[1]. The acoustic phonon inter-subband relaxation rate from a fixed initial state subband at $\mathbf{k}_{\parallel} = 0$, where $\mathbf{k}_{\parallel}$ is the in-plane quasi-momentum, to a lower energy final state as a function of the final state $\mathbf{k}_{\parallel}$, shows intricate oscillatory behavior reflecting the multiband admixed nature of the wavefunctions. The type of oscillatory behavior depends markedly on the QW growth direction, as for a [001] growth direction well defined parity states can be defined, while for lower symmetry directions this is no longer possible. Strong in-plane hole subband anisotropy effects on acoustic phonon relaxation rates have also been investigated for lower symmetry growth directions, motivated by recent magneto-tunneling experiments on [311]A QWs[2].

[1] K. Greipel and U. Rössler, Semicond.Sci.Technol. 5, 487 (1992).
[2] R.K. Hayden *et al.*, Phys. Rev. B, **46**, 15586 (1992).

Tup4 Number and current fluctuations as a probe for contact modeling of ballistic one-dimensional structures, Tilmann Kuhn, *Institut für Theoretische Physik, Universitat Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart, Germany;* Lino Reggiani,*Dipartimento di Fisica ed Islituto Nazionale di Fisica della Materia, Universitá di Modena, Via Campi 213/A, 41100 Modena, Italy;;* Luca Varani, *Centre d'Electronique de Montpellier, Université des Sciences et Techniques du Languedoc, 34095 Montpellier Cedex 5, France.* In this communication we report a theoretical investigation on the fluctuations of carrier number and current in one-dimensional ballistic structures at different degrees of degeneracy. We are particularly interested in phenomena related to the finite transit time of the carriers from one contact to the other and thus in the high-frequency behavior of the noise spectrum. In the time domain, the analysis of the correlation functions as a function of an external applied voltage show peculiar features in passing from a classical to a completely degenerate condition which can be summarized as follows. For a classical system these functions exhibit a non-exponential behavior with characteristic long-time tails associated with the deterministic features of a ballistic transport. For a degenerate system, the presence of the Pauli factor $f(1-f), f$ being the Fermi distribution, is found to be responsible for peaked values of the variances at given values of the applied field. In the frequency domain, the corresponding spectral densities exhibit non-Lorentzian decay with peculiar geometrical resonances for the degenerate conditions. The present investigation is found to be quite appropriate to exploit the essential importance of the contact modeling in determining the transport properties of ballistic structures.

Wednesday, April 27

Wa1 (Invited) High Resolution Microscopy of Interfaces in Thin Film Hetero-structures, Zuzanna Liliental-Weber, *Center for Advanced Materials, Materials Science Division., Lawrence Berkeley Laboratory 62/203, University of California, Berkeley, CA 94720.* The results of elastic strain relaxation and its effect on

interface roughness and defects formed at the interface for systems with increasing misfit will be discussed. The details of interface structures will be shown with resolution better than 2 Å using state-of-the-art transmission electron microscopes. Several systems will be discussed starting from homoepitaxial-layers GaAs/LT(low-temperature grown)-GaAs where only 0.1% misfit is present between the layers, followed by the study of hetero-interfaces such as LT-GaAs/AlAs/LT-GaAs, then $In_{0.2}Ga_{0.8}As$ grown on GaAs with 1.4% misfit, and GaAs/Si with 4% misfit, and finally GaAs/InAs/GaAs with 7% misfit. For *In* rich layers grown on GaAs the anisotropy of α and β dislocation introduction was observed. This anisotropy was drastically enhanced by substrate tilting. Outdiffusion of *In* (toward the surface and into the substrate) was observed even for layer thickness below the critical layer thick-ness for misfit dislocation introduction. This *In* diffusion also resulted in formation of platelets rich in *In* near the InGaAs/GaAs interface, and the decoration of misfit dislocations by *In*. The local strain associated with such platelets may be large enough for the nucleation of dislocation loops which can be considered as a source of misfit dislocations. Anistropy of dislocation types as well as their distribution was also observed for GaAs grown on Si where dislocations along [110] are mostly edge type and along [-110] many partial dislocations are formed with stacking faults extended into GaAs. Location of misfit dislocation cores some of which are located within the substrate will be discussed for InGaAs grown on tilted GaAs substrates and for GaAs grown on Si. For the layers with the highest misfit (InAs/GaAs) only one of two monolayers can be grown before three-dimensional growth starts to take place. Formation of different types of dislocations during three-dimensional island growth will be discussed. Finally, the relation between the interface roughness and carrier scattering in devices will be presented.

Wa2 Hydrogen Passivation of Near-Surface GaAs/AlGaAs Unstrained Quantum Wells, Ying-Lan Chang, I-Hsing Tan, Wolf Widdra, Sang I. Yi, James Merz, Evelyn Hu and Henry Weinberg, *Center for Quantized Electronic Structures (QUEST)*, University of California, Santa Barbara, CA 93106. Effective passivation of surfaces can be a critical determinant of the electrical and optical performance of semiconductor devices. This is particu-larly true for low dimensional structures, which have high surface-to-volume ratios. We have used a near-surface $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well (QW) as an effective probe of surface states after various surface treatments [1]. The AlGaAs barrier layer separating the QW from the surface was varied from 350 A to 60 A by wet-etching. The decrease of the surface barrier layer results in a systematic reduction in luminescence of the near-surface QW. Hydrogenation of such structures with an ion source in general resulted in improved luminescence intensity, even for small values of barrier layer thickness. The hydrogen treatment involved 100 eV, at a range of ion doses and substrate temperatures. We find that surface state passivation is readily achieved at room temperature and very low H-dosage ($10^{16}cm^{-2}$), with an observed recovery of the free-exciton emission in the near-surface QW. The surface passivation effect was found to be stable for up to six months in air. Hydrogen treatments with higher doses and/or higher temperatures also produced enhanced luminescence through the penetration of hydrogen into the bulk material, and consequent improvement of material quality [2]. *In situ* Auger electron spectroscopy shows that hydrogen treatment with H-ions produces a modified, Ga-rich surface, with no significant change of oxygen concentra-tion. The correlation between surface chemistry and luminescence efficiency suggests that the optical properties of the near-surface QW are dominated by the quality of the interface between the AlGaAs surface barrier and the overlying oxide. The possible mechanism of passivation is the removal of As from the interface, therefore, the reduction of the Asantisite defect which is the dominant defect for an oxide-contaminated surface [3]. The Ga-oxide and/or Al-oxide layer serves as a passivation overlayer, and is responsible for the long-term stability of passivation effect. Support of this hypothesis is found in our experiments involving hydrogenation of near-surface QW samples utilizing *atomic* hydrogen. Both the resulting surface chemistry and the effect on luminescence of the near-surface QW were dramatically different from the experiments that utilized hydrogen ions. The recovery or enhancement of luminescence efficiency after different degree of hydrogenation offers hope for better controlled surfaces that should improve the performance of low-dimensional systems such as quantum wires and dots. These experiments help to underline the sensitivity of the structures themselves and attempt to better understand the mechanism of effective hydrogen surface passivation.

[1] Yin-Lan Chang, et al, Appl. Phys. Lett. **62**, 2697 (1993).

[2] Ying-Lan Chang, et al., J. Appl. Phys. **74**, 5144 (1993).

[3] W.E. Spicer, et al., J. Vac. Sci. Technol. **B6**, 1245 (1988).

Wa3 Photoluminescence Character-ization of Sidewall Surfaces in Dry-Etched InGaAs/InP Quantum Wires and Dots,* S.Q. Gu, E. Reuter, Q. Hu, H. Chang, R. Panepucci, I. Adesida, S.G. Bishop, *Center for Compound Semiconductor Microelectronics, Materials Research*

Laboratory, and Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, IL 61801, and C. Caneau and R. Bhat, *Bell Communication Research, Red Bank, New Jersey 07701.* High resolution electron beam lithography and reactive ion etching in methane-hydrogen plasmas (CH_4/H_2 have been used to fabricate InGaAs/InP open quantum well wires (QWW) with widths ranging from 100 to 40 nm, and quantum dots (QD) with diameters ranging from 600 to 100 nm. These nanostructures were fabricated on a MOVPE-grown, lattice-matched InGaAs/InP (5 nm thick InGaAs quantum well layer) quantum well (QW) heterostructure. Their lateral dimensions range from the regime for which the optical spectra may be manifestations of reduced dimensional, bulk-like properties, to the regime dominated by the effected of the sidewall surfaces. The quest for spectral and intensity manifestations of the effects of confinement or lowered dimensionality in mesoscopic structures is often confused by a variety of effects which are related to QWW and QD sidewall surface defects. In addition to the obvious quenching of PL efficiency by sidewall surface recombination, there are several spectral effects which are a function of excitation intensity. These include: band bending near sidewall interfaces which can be flattened at high excitation intensity; the effects of band filling in k-space and band gap renormalization due to many-body effects; and inhomogeneities in lateral QWW and QD dimensions. In an attempt to delineate or isolate the over-lapping effects of reduced dimensionality and sidewall surfaces in our QWW and QD, the peak energies, efficiency, and lineshapes of their low temperature (5K) photoluminescence (PL) spectra have been investigated as a function of lateral dimension and excita-tion laser power. The excitation power dependence of the PL energies and lineshapes in relatively wide wires (~100 nm) and large diameter dots(~300 nm) exhibits the effects of band filling in k-space and band gap renormalization due to many-body effects as reported for dense electron-hole plasmas (EHP) in two-dimensional (2D) semiconductor structures (QW mesas) for similar excitation intensities [1]. Thus, surface recombination in these wide QWW and larger QD does not limit the attainable photoexcited EHP density. In contrast, the power dependence of the PL lineshape for the narrowest wires studied (~40 nm) is dominated by the effects of sidewall surface recombination which limit the attainable EHP density. These effects are also evident in the precipitous drop of PL efficiency for QWW widths less than ~80 NM and QD diameters less than ~170 nm. These data are compared with the simple surface depletion model [2] using the values of S (surface recombination velocity) and t (thickness of optical dead layer) as fitting parameters. The QWW PL spectra also exhibit a 2 meV blue-shift as the wire width decreases to 40 nm, consistent with results reported for buried InGaAs/InP wires of the same width [3]. In the QD the blue-shift of the PL peak reaches 10 meV as their diameters decrease to 100 nm which is larger than the value predicted by theory for these dot sizes.

* Supported by the National Science Foundation (ECD 89 43166 and DMR 89-20538) and the Office of Naval Research University Research Initiative Program (N00014-92-J-1519).

[1] V.D. Kulakovskii, E. Lach, A. Forchel and D. Grutzmacher, Phys. Rev. B **40**, 8087 (1989).

[2] A. Forchel, A. Menschig, B.E. Maile, H. Leier and R. Germann, J.Vac Sci. Technol. B, **9**, 444 (1991).

[3] M. Notomi, M. Naganuma, T. Nishida, T. Tamamura, H. Iwamura, S. Nojima, and M. Okamoto, Appl. Phys. Lett. **58**, 720 (1991).

Wa4 Structures and Properties of Self-Assembled InGaAs Quantum Dots, S. Fafard, D. Leonard, G. Wang, Y.H. Zhang, J.E. Bowers, J.L. Merz, and P.M. Petroff, *Center for Quantized Electronic Structures (QUEST), University of California, Santa Barbara, CA 93106.* A novel method for the production of quantum dots is presented[1,2]. The method exploits the mismatch strain of MBE deposited InGaAs on GaAs to induce a transition from the two dimensional growth mode to the three dimensional (Stranski-Krastanow) growth mode. The role of strain in making uniform the InGaAs cluster sizes will be examined. The cluster size is limited to quantum dimensions by precisely controlling the amount of InGaAs that is deposited in order to cause the growth mode transition. Very narrow size distributions (±10%) have been obtained. The diameter and areal density of these clusters are adjustable by choosing the deposition parameters. Smooth MBE growth of GaAs over these clusters produces a layer of quantum dots whose high quality can be easily observed with transmission electron microscopy and atomic force microscopy. The photo-luminescence (PL) emitted from the dots at around 1.2eV is of intensity comparable to that of a reference quantum well. Resonances in photo-luminescence excitation (PLE) spectra suggest that the density of states in these dots has minima close to zero between the quantum states as expected for a zero dimensional system. These PLE peaks shift with the detecting energy, showing that by changing the detecting energy, we are sampling different sizes of dots. The temperature dependence of the PL indicates that the exciton binding energy in these 20 nm diameter quantum dots is enhanced by a factor of 2 as compared to a quantum well, due to the lateral confinement. In PL and PLE of all samples, there is virtually *no* overlap between the emission and the absorption energies of the quantum dots. This effect remained

for all excitation intensities used, suggesting that this is an intrinsic property of these dots. Further optical evidence for the existence of lateral confinement in the dots will be presented, demonstrating that this in-situ technique produces high quality dots of quantum size. Magneto capacitance and IR absorption data that confirm the OD properties of these structures will be presented.

[1] D. Leonard, M. Krishnamurthy, S. Fafard, J.L. Merz, and P.M. Petroff, Journal Vac. Sci. Tech. to be published.

[2] D. Leonard, M. Krishnamurthy, C.M. Reeves, S.P. Denbaars, and P.M. Petroff, Appl. Phys. Lett., to be published Dec. 6 (1993).

Wa5 Si-interlayer Based Interface Control Technology for Compound Semiconductor Mesoscopic Structures, H. Hasegawa, S. Kodama, S. Kasai, K. Sasaki and H. Fujikura, *Research Center for Interface Quantum Electronics and Dept. of Electrical Engineering, Hokkaido University, North 13 West 8, Sapporo, 060 Japan*. In mesoscopic structures, potential differences at surfaces and interfaces are directly utilized as the boundary conditions for electron wavefunctions. Thus, requirements for the "electronic perfection" of surfaces and interfaces are much more stringent than in the present-day devices. However, in compound semiconductor technology, reasonably well controlled interfaces can only be obtained by continuous growth of very similar materials like GaAs and AlAs. Interface formation between dissimilar materials to obtain larger potential differences, or interface formation through crystal regrowth, thin film deposition, electron and ion beam processes and dry etching *etc.* results in formation of surface or interface states which cause Fermi level pinning and strongly interact with mesoscopic behavior of electrons. For example, the reported voltage control of quantum wires by a side gate[1] suggests involvement of surface states, indicating that the side-gating phenomenon, which is a long standing issue in GaAs LSIs, may also become a problem in planar integration of mesoscopic structures. Thus, control of interface by suitable means is a key issue for success of mesoscopic devices and their planar integration. The purpose of the present paper is to present and discuss a novel Si-interlayer based interface control technology which is being developed at our Research Center for successful control of various interfaces of compound semiconductor mesoscopic structures. In this approach, an ultrathin Si interface control layer (Si ICL) is inserted at the interface in order (1) to establish an ordered atom arrangements at the interface so as to remove interface states and (2) to control the interface potential by built-in dipoles in the Si ICL. Main points are listed below.

(1) Various sample structures having Si ICLs were formed using a UHV-based total system where MBE, GSMBE, CVD, ECR, EB/FIB, PL, XPS/UPS and STM chambers were connected by a UHV-transfer chamber. Si ICL was grown by MBE, using a Si K-cell. Such a system without air exposure during processing was found to allow formation of structures with the interface "atomic" profiles monitored and controlled to a monolayer-level. A novel PL surface state spectroscopy was also developed for ***in-situ*** monitoring of the "electronic" properties of surface and interfaces during formation of Si ICLs and related quantum structures.

(2) Insertion of Si ICL of 10 Å at the insulator-semiconductor interfaces of GaAs and InGaAs greatly reduced inter-face state density and removed Fermi level pinning. Direct application of Si ICL to InGaAs wire structures formed by selective epitaxy greatly increased the intensity of PL emission from wires as compared with those without Si ICL. Strong interaction between surface states and near-surface AlGaAs/GaAs and InGaAs/GaAs quantum wells, recently observed by our group[2], was very much suppressed by the Si ICL technique. Application of Si ICL to the surface of semi-insulating GaAs substrate reduced surface-related leakage current and increased surface breakdown field strength which is related to the side-gating threshold.

(3) Insertion of Si ICL of 10 Å with suitable doping at metal-semiconductor interfaces of GaAs and InP was found to allow control of Schottky barrier heights over 300-400 meV by doping-induced dipoles with retaining nearly ideal thermoionic current transport. This opens up a possibility of a large-amplitude potential modulation for mesoscopic structures. Application of such a technique to modification of heterojunction band line-up is also discussed.

[1] T.J. Thornton and Y. Feng: Inst. Phys. Conf. Ser. **127,** 111 (1992).

[2] Z. Sobiesierski, D.I. Westwood, D.A. Woolf, T. Fukui and H. Hasegawa: J. Vac. Sci. Technol. **B11,** 1723 (1993).

Wa6 Air-bridges and Sub-Micron Gating: A Key Fabrication Technology for Mesoscopic Devices, M.E. Sherwin, J.A. Simmons, J.F. Klem and R. Corless, *Sandia National Laboratories*, Albuquerque, NM 87185-0603*. As electronic devices based on quantum effects mature, present fabrication technologies are often pushed beyond their limits. In particular, the need for independently contacted sub-micron metal is difficult to achieve with conventional contacting technology. Furthermore, the functionality of many mesoscopic devices prevents the use of contacting schemes that use metal wiring running on the device surface. Recently, contacting schemes have been developed

which utilize a dielectric spacer layer (either SiO_2 or SiN_x)[1] and multiple metallization steps with very tight tolerances on inter-level registration accuracy. However, it is well known that the presence of a dielectric layer on a GaAs surface can greatly modify the surface states which can have undesired effects on the underlying device structure. In addition, the processing associated with the deposition and etching of dielectrics is often damaging to the GaAs surface. We have developed a single step metallization process that is capable of producing sub-micron gate contacts without the need for dielectric spacer layers. Using a selective exposure/development electron beam lithography process with a bilevel resist profile, we can create air-bridge structures that are 0.5 µm above the semiconductor surface. These air-bridges are made with 700 nm of evaporated Ti/Au and exhibit excellent integrity and strength, showing no difficulty in spanning over 20 µm between support posts. The metal is deposited in a single evaporation and liftoff step. With the above dimensions, contact posts can be fabricated with diameters of 150 nm. Additionally, the process is self planarizing due to the resist spin-on and therefore no difficulty is encountered in bridging first level metal or etched semiconductor steps. This novel contacting process allows the fabrication and development of novel mesoscopic devices that previously presented serious fabrication difficulties. To investigate the applicability of our process we have used a sub-micron contact post in the fabrication of the island-in-the-strait geometry[2] with an independently contacted center island. Low temperature measurements have clearly shown the formation of two parallel quantized conductance channels on either side of the center island. The parallel channels can be modulated by either side gate or in parallel by the central contact post. The ability to independently bias all three gate offers greater flexibility in fabrication and experimentation. This fabrication technique will have great utility for quantum dot and anti-dot experiments and single electron energy spectroscopies. Preliminary data on the island-in-the-strait device at high magnetic fields and further application of our process to additional structures will be presented.

* This work was performed at Sandia National Laboratories in the Compound Semiconductor Research Laboratory and was supported by the Dept. of Energy under contract #DE-AC04-94AL85000.

[1] R.P. Taylor et al., J. Vac. Sci. Technol. B Vol. 11, No. 3, pp. 628-633 (1993).

[2] J.A. Simmons et al., Superlattices and Microstructures Vol. 11, No. 2, pp. 223-227 (1992).

Wp1 Low-Dimensional Resonant Tunneling and Coulomb Blockade: A Comparison of Fabricated Versus Impurity Confinement, M.A. Reed, M.R. Deshdande, E.S. Hornbeck, and N. Dekker, *Yale University, New Haven, CT 06520.* Nanometer scale fabrication techniques, combined with epitaxial resonant tunneling structures, now routinely allow the study of quasi-0D confined electron systems. In addition to energy level separations that are tunable by the confining potentials, these systems can also exhibit Coulomb blockade. We have fabricated a series of novel InGaAs "vertical" quantum dots which are specifically designed to allow (and indeed exhibit) an interplay between dimensional quantized levels and Coulomb blockade levels. Spectro-scopy is presented which distinguishes between the effects. Additional finer structure is observed, and is interpreted as due to irregularities in either the surface potential or dopant profile. Surprisingly similar I(V) and G(V) characteristics have previously been reported for larger, confined resonant tunneling devices. We have found that some characteristics exist regardless of the lateral confinement, and that the turnon characteristics of nearly all resonant tunneling devices exhibit sharp peaks in conductance. These have previously been attributed to lateral confinement; we show that instead these are attributable to tunneling through single quantum well donor states. We have performed electronic spectroscopy of these states, and find binding energies as large as 10-20 meV greater than expected for a single quantum well donor, with corresponding intrinsic linewidths ~0.5 meV. These unintentional donor states are distributed in energy, dependent on both donor position in the quantum well and quantum well width fluctuations. These states also exhibit finer structure, and a comparison of these versus fabrication-confined structures will be presented.

Wp2 Resonant Magnetotunneling Spectroscopy of InAs/GaSb/AlSb Interband Tunneling Diodes, R.R. Marquardt, D.A. Collins, Y.X. Liu, D. Z-Y. Ting, and T.C. McGill, *T.J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology 128-95, Pasadena, CA. 91125.* The InAs/GaSb/AlSb material system offers many advantages for use in mesoscopic devices. Many of these advantages are due to the staggered-gap band alignment between InAs and GaSb, whereby the valence band edge of GaSb lies higher in energy than the conduction band edge of InAs. As a consequence, charge transfer between these materials dopes adjacent layers without the stochastic behavior of impurities in small-scale structures. Also, a wide variety of device structures involving both electron and hole transport have been demonstrated in this system, with useful operating characteristics persisting to room temperature.[1] We have studied three InAs/AlSb/GaSb/AlSb/InAs resonant interband tunneling (RIT) diodes in transverse magnetic fields up to 8 tesla. In this device, transport involves

resonant tunneling of electrons from the InAs emitter, through unoccupied electron states in the subbands of the GaSb well, and subsequently back into the conduction band of the collector. The change in the transverse momentum distribution of carriers induced by the magnetic field is used in resonant magnetotunneling spectroscopy[2] (RMTS) to probe the energy subband dispersion in the GaSb well. The three samples we studied had 4.0 nm AlSb barriers, with 7.0 nm, 8.0 nm, and 11.9 nm wide GaSb wells, respectively. In all three samples, we observed classic RMTS behavior only for fields greater than a sample-dependent critical magnetic field.[3] Below this critical field, the current-voltage characteristics showed little effect from the magnetic field. While the exact nature of this abrupt transition is unknown, we believe it to be due to a change in the dimensionality of the emitter electrons; below the critical field the source distribution is 3D, while above the critical field, the electrons are confined in a notch state at the InAs/AlSb interface, and obey a 2D distribution. The nature of this transition, and its implications for mesoscopic structures, are important to the full understanding of quantum transport in this system.

[1] D.A.Collins et al., in Resonant Tunneling in Semiconductors: Physics and Applications, edited by L.L. Chang, E.E. Mendez, and C. Tejedor (Plenum, New York, 1991).

[2] R.K. Hayden et al., Phys. Rev. Lett. 66, 1749 (1991).

[3] R.R. Marquardt et al., to be submitted to Phys. Rev. B.

Wp3 Equilibrium and Nonequilibrium Charge Distributions at Semi-conductor-Semiconductor and Semi-conductor-Metal Heterointerfaces via the Quantum Liouville Equation*, H.L. Grubin and R.R. Govindan, *Scientific Research Associates, Inc., Glastonbury, CT. 06033,* and D.K. Ferry, *Arizona State University, Tempe, AZ. 85287-6206.* While many device treatments of semiconductor-semiconductor interfaces typically include quantum contributions, less device work has been done on the quantum contributions at Schottky barrier interfaces or at the more prosaic pn interface. Yet in some of these cases quantum contributions as measured by the Bohm or Wigner quantum potential indicate very significant quantum effects. For example, through device simulations utilizing the quantum Liouville equation in the coordinate representation, we have represented the Schottky barrier as a *metal-semiconductor heterojunction*, with the barrier height being built up through a combination of work function differences and interface states. We have also introduced local clusters of charge examining their influence on the barrier. The resulting structure is analyzed through three different quantum based calculations: (a) quantum capacitance calculations, (b) current voltage calculations, and (c) the quantum potential. The following observations are noted: The quantum potential calculations indicate that over a range of 2nm from the interface, quantum contributions are of the order of the barrier height, and must be included in any study of Schottky barriers. Second, in the model in which interface states are included, the effects of local clusters of charge can result in a local and partial collapse of the depletion region. In addition to the above observations a significant advance of the Liouville equation simulations is an ability to include dissipation and to examine the effects of finite but small current on CV studies. A variety of calculations are being performed to illustrate the above contributions, and the effects of varying device parameters will be discussed. Additional calculations with pn heterojunctions will also be discussed.

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Wp4 One-Dimensional Strong Correlation Effects on Nanometer-Size Quantum Wire Device Performance, Sankar Das Sarma, *Department of Physics, University of Maryland, College Park, MD, 20742-4111.* I will address the issue of the peculiar effects of one dimensionality on the device performance of semiconductor quantum wire structures. In particular, several exact field-theoretic results (due to Tomonaga, Luttinger, Haldane, Anderson, Mattis-Lieb, Luther-Emery and others) suggest that a strictly one-dimensional electron system is singular with no Fermi surface and with spin-charge separation in the collective elementary excitation spectra. I will discuss the extent to which these exact (and rather sophisticated) theoretical considerations could affect the projected quantum wire device applications. An issue of particular significance is whether modeling and simulation of quantum wire devices must include these exact results (which would be a formidable task). I will emphasize how the details of the actual confinement (i.e., the role of various surfaces and interfaces) would be of paramount importance in sorting out these issues. My talk will mostly consider the role of interfaces in many-body effects and quantum transport properties of nanostructured quantum wires.

Wp5 Persistent Currents in Finite-Width Mesoscopic Multi-Channel Rings, L. Wendler and V. M. Fomin, *Fachbereich Physik, Martin-Luther-Universität Halle, Germany.* Advances in nanometer technolgies make it possible to confine the carriers in a controlled way in submicron devices, such as mesoscopic normal-metal wires and rings, semiconductor structures such as quantum wells, quantum-well wires, quantum dots and rings. The

study of the transport propeties of *mesoscopic* normal-metal and semiconductor devices is proved to be a rich source of novel interesting phenomena. In the last time special attention is directed to the persistent current problem in mesoscopic normal-metal and semiconductor rings threaded by an Aharonov-Bohm (AB) flux Φ. We have developed a theory of persistent currents for finite-width mesoscopic multi-channel rings with impurities both threaded by an AB flux and in the presence of a magnetic field penetrating the ring. The energy band structure and the persistent currents are calculated using two different methods: (i) the *diagonal approximation* and (ii) the K_{max}-*channel approximation*. We have performed analytical and detailed numerical calculations to study the energy bands and the persistent currents in dependence on the width of the ring and the radial and azimuthal impurity positions. Due to the *inter-channel* interaction in the finite-width mesoscopic rings the persistent currents acquire a rich structure of harmonics. The mostly expressed is the second harmonic of the persistent current. This fundamental result of the period halving does not involve any kind of statistical averaging and rests on the account of the interaction between the radial and azimuthal motion of an electron due to the impurity scattering in the *finite-width* mesoscopic multi-channel ring. Special attention is directed to the interfaces of the ring. We investigate the energy band structure and persistent currents for two types of confining potential, hard-wall and soft-wall potentials in the radial direction.

Thursday, April 28

Tha1 (Invited) Capacitance and Electronic Structure of Quantum Dots, M. Macucci, *Dipartimento di Ingegneria dell' Informazione, Universitá degli Studi di Pisa, Via Diotisalvi 2, I-56126 Pisa, Italy.* Quantum dots, whose fabrication has become feasible with modern nano-lithographic techniques, offer an unprecedented opportunity to observe the behavior of electron systems with quantum confinement and Coulomb interaction energies of the same order of magnitude. We have computed the electron removal energies and the capacitance for two-dimensional model quantum dots with rectangular or circular symmetries. The Schrödinger equation has been solved self-consistently, with the inclusion of many-body effects within the framework of the Local Density Approximation. Although our calculation is performed for a temperature of 0 K, the results for the capacitance are directly comparable with the experimental values. Such values can be deduced from the spacing of the conductance peaks experimentally observed between two leads loosely coupled through a quantum dot, and the effect of a finite temperature is only a broadening of the conductance peaks. Our results show a smooth transition from a quantum dominated regime characteristic of smaller dots, in which the confinement energy is prevalent, to a substantially capacitive behavior typical of dots larger than a few hundred nano-meters. Experimental results are not yet available for small dots, but some of the trends predicted by our model are already recognizable in the data collected by several groups. The effect of a conducting gate on the dot capacitance has been included in our calculations by means of the method of images. We have found that for realistic structures the main contribution to capacitance comes from the self-capacitance of the dot, and only corrections are due to the presence of the gate.

Tha2 Non-equilibrium Transport in Lateral Double Constriction Devices*, C. Berven and M.N. Wybourne, *Physics Dept., Univ. of Oregon, Eugene, OR 97403,* S.M. Goodnick and N. Harff, *Dept. of Electrical and Computer Engr., Oregon State Univ., Corvallis, OR 97331,* and D.D. Smith, *Army Research Lab, Fort Monmouth, NJ 07703.* Lateral double constriction devices with a quantum dot containing about 100 to 300 electrons have been constructed that display two distinctly different types of current-voltage characteristics. As reported earlier[1], the first type of current-voltage characteristic shows S-type negative differential conductance. This behavior is attributed to the heating of the electrons in the dot by the conduction electrons. When a critical electron temperature is reached, the current dramatically increases and is responsible for the bistability of the current-voltage characteristics. The second type of current-voltage characteristic is attributed to the quantized conduction of the electrons through the quantum point contacts at the entrance and exit to the quantum dot. This behavior is understood when the carrier heating is suppressed such that the dot remains close to thermal equilibrium. The current voltage characteristics are explained with the use of an energy balance approach as well as a three dimensional semi-classical Monte Carlo model for transport through the dot.

* Work supported by grants from the National Science Foundation No. ECS 9216768 and ONR.

[1] J.C. Wu, M.N. Wybourne, C. Berven, S.M. Goodnick and D.D. Smith, Appl. Phys. Lett. 61, 2425 (1992).

Tha3 Numerical Simulation of Electron Confinement in Quantum Dot Structures*, Minhan Chen and Wolfgang Porod, *Dept. of*

Electrical Engineering, University of Notre Dame, Notre Dame, IN. 46556. We present potential distributions and quantized electronic states in gated AlGaAs/GaAs quantum dot structures obtained from self-consistent solutions of the axisymmetric Poisson and Schrödinger equations. Our model takes into account the effect of surface states by viewing the exposed surface as the interface between the semiconductor and the dielectric[1]. We investigate the occupation of the quantum dot structures as a function of (i) gate bias, (ii) distance of the confining heterointerface from the top gate, and (iii) different physical models of the interface charge at the exposed semiconductor surface. This modeling is important for the design of recently proposed mesoscopic computing architectures[2], called Quantum Cellular Automata, which consist of arrays of interacting quantum dot cells occupied by few electrons.

* Supported in part by ARPA/ONR and AFOSR.

[1] M. Chen, W. Porod, and D.J. Kirkner, J. Appl. Phys. (March 1994).

[2] C.S. Lent, P.D. Tougaw, W. Porod, and G.H. Bernstein, Nanotechnology **4**, 59 (1993).

Tha4 High Bias Transport Through Quantum Dots, Gerhard Klimeck, Roger K. Lake, Supriyo Datta, *Purdue University, School of Electrical Engineering, West Lafayette, IN 47907-1285*, and Garnett W. Bryant, *U.S. Army Research Laboratory, Microphonic Device Branch, Adelphi, MD 20783-1197.* Starting from a rate equation model proposed by Beenakker we calcu-late the current-voltage characteristics including the effects due to discrete subbands in the leads, inelastic scattering and single-electron charging within a single quantum dot. In a numerical calculation we analyze quantum dots with up to 26 electrons. We show in three independent examples how single-electron charge interaction. Inelastic scattering, and non-adiabatic subband mixing can enhance the valley current significantly by opening new conduction channels. Our analysis shows that symmetric structures with weak charge accumulation still shows additional fine structure due to single-electron charging with little changes due to inelastic scattering. But the I-V-characteristic of asymmetric structures is shown to depend critically on the strength of the inelastic scattering in the quantum dot.

Tha5 Interface Binding and Quantum Dot Self-Consistent Electronic Structure, M. Stopa, Y. Aoyagi and T. Sugano, *The Institute for Physical and Chemical Research, RIKEN, Saitama Ken 2-1 Hirosawa, Wako-Shi.* Mesoscopic devices fabricated on an electron gas formed at a semiconductor interface are routinely treated by theorists as ideal two dimensional systems. Analysis of electron scattering rates, tunneling coefficients, edge state formation and level spectra frequently ignore the electronic structure in the growth direction (z-direction) altogether. A full three dimensional analysis of the self-consistent electronic structure of a lateral semiconductor quantum dot, however, reveals that several experimentally relevant device characteristics depend on the width and the structure of the electron wave functions in the z-direction. In this paper we present the results of our full self-consistent electronic structure calculation for a lateral semiconductor quantum dot containing up to $N \sim 100$ electrons in a transverse magnetic field. In the Coulomb blockade regime for transport through the dot, two of the device characteristics of particular relevance are the device capacitance matrix and the tunneling coefficients between the dot and the leads. Both of these characteristics are strongly influenced by the quasi two-dimensional nature of the system. The capacitance between the dot and the source drain 2DEG leads has been a subject of considerable debate recently [1]. As the quantum point contact (QPC) tunnel barriers become narrow on the scale of the width of the wave functions in the z-direction we show that the lead to dot capacitances increase and eventually dominate the device electrostatics. As a result, the charging energy becomes quenched and a transition occurs to an unblockaded regime. With regard to tunneling, it has not been fully recognized that, beneath a QPC barrier, or indeed in any depleted region, electrons are not bound to the interface at all. Therefore, tunneling through a barrier in a 2DEG system involves a motion of the electron *away from the interface* and into the bulk. We show that in this case a full treatment of the interface binding effects is necessary to understand the transmission through such a barrier and hence through the device as a whole.

[1] E.B. Foxman, P.L. NcEuen, U. Meirav, N.S. Wingreen, Y. Meier, P.A. Belk, N.R. Belk, M.A. Kastner and S.J. Wind, Phys.Rev. B **47**, 10020 (1993).

Tha6 Electrical Transport in the Quantum Dot in the Edge State Regime, K. Ishibashi, J. P. Bird, M. Stopa, C. Barnes, T. Sugano and Y. Aoyagi, *Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-01, Japan.* We have formed quantum dots in the GaAs/A1GaAs 2-dimensional electron gas by applying the negative gate voltage on the split metal gates fabricated on top of the wafer by using the electron beam lithography and the lift off technique. The magnetoresistance has been measured in the temperature range from 10mK to 1.2mK under the magnetic field up to 8 T. The clear quantum Hall plateaus are observed without the gate voltage, however, once dot structures are formed, the complicated structures are observed both on plateaus and in the transition regions. In the low magnetic field, where perfectly transmitted edge states

exist, the resonant like structures are observed on the quantum Hall plateaus. The peak height decreases as the temperature is increased, and the structures disappear in 1.2K. These resonant structures are attributed to the resonant transmission through the localized edge state loop. The temperature dependence of the resonant peaks may give information on the phase breaking process in the edge state regime. In the high magnetic field, where the dot is isolated from the outside due to the depopulation in the point contacts, the periodic oscillations are observed in the magnetoresistance. The period of the oscillations does not depend on the gate voltages applied to the split gates, but changes easily by the thermal cycling. The period is much larger than the expected period due to the AB mechanism related to the localized edge state loop. We explain these oscillations by using the coulomb blockade mechanism.

Tha7 Time Constant for an Atomic Relay Computed by Ab Initio Molecular Dynamics, P. von Allmen and K. Hess, *Beckman Inst. for Advanced Science and Technology, University of Illinois at Urbana-Champaign.* Recent progress in the manipulation of single atoms has prompted realistic efforts in the conception of novel devices with single atoms as their basic components. Y. Wada and co-workers[1] proposed a struc-ture for an atomic relay where the switching element is one single atom. It consists of a chain of atoms from which one atom can be moved through an electric field applied by two other chains situated perpendicularly. With a simple tight-binding model they showed that the current flowing in the wire can be interrupted if one atom is removed. They claim that the time response of such a device should be in the THz regime by reference to the oscillation frequency of an atom in a solid. We made one further step towards a realistic model for this device. In our model the silicon atoms are localized by an harmonic potential which was deduced from the restoring forces acting on the atoms at a silicon (001) surface. An oscillating electric field is then applied through the lateral chains and the response of the moving atom is studied in detail. Our work gives interesting insight into the potential applications of such a device. For this study we used our *ab initio* molecular dynamics program that was developed following the ideas of R. Car and M. Parrinello[2]. The forces acting on the atoms are computed using the Hellman-Feynman theorem and fully include the contribution from the ions and the electrons. The electrons are described within the density functional formalism and we use first-principle non-local pseudopotentials.

[1] Y. Wada, T. Uda, M. Lutwysche and S. Kondo, 1993 International Conference on Solid State Devices and Materials, Chiba, Japan.

[2] R. Car and M. Parrinello, Phys. Rev. Lett. **55**, 2471 (1985).

Friday, April 29

Fa1 (Invited) Quantum Cellular Automata, Craig S. Lent, *Dept. of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556.* I will discuss a new paradigm for computing with cellular automata (CA) composed of arrays of quantum devices - quantum cellular automata (QCA). Computing in such a paradigm is edge-driven. Input, output, and power are delivered at the edge of the array only; no direct flow of information or energy to internal cells is required. Computing in this paradigm is also computing with the ground-state. The architecture is so designed that the ground state configuration of the array, subject to boundary conditions determined by the input, yields the computational result. We have examined a specific realization of these ideas using two-electron cells composed of quantum dots, which is within the reach of current fabrication technology. The charge density in the cell is very highly polarized (aligned) along one of the two cell axes, suggestive of a two-state CA. The polarization of one cell induces a polarization in a neighboring cell through the Coulomb interaction in a very nonlinear fashion[1]. This basic interaction is exploited to make QCA wires which transmit binary information encoded in the polarization state of the quantum cells[2]. We show how logical gates can be constructed using the same cell-cell coupling mechanism. The device modeling we perform by solving the two-electron Schrödinger equation directly for each cell. Arrays of cells are modeled using a self-consistent Hartree technique based on the two-electron problem in each cell. We show how useful computing structures might be built from a set of logical primitives composed of quantum cells. This set includes wires, wire crossings, inverters, and a flexible three-input structure[3]. The three-input device can be configured as an AND gate, an OR gate, or a majority logic unit. The configurability of the three-input device, which can be programmed to switch between an AND and an OR gate, offers exciting new design possibilities[4]. Devices as complex as single-bit full adders have been simulated.

[1] Craig S. Lent, P. Douglas Tougaw, and Wolfgang Porod, Applied Physics Letters **62**, 714 (1993).

[2] Craig S. Lent and P. Douglas Tougaw, Journal of Applied Physics **74**, 6227 (1993).

[3] P. Douglas Tougaw, Craig S. Lent, and Wolfgang Porod, Journal of Applied Physics **74**, 3558 (1993).

[4] Craig S. Lent, P. Douglas Tougaw, Wolfgang Porod, and Gary H. Bernstein, Nanotechnology **4**, 49 (1993).

Fa2 Chemical Patterns as Building Blocks for Mesoscopic Structures, B. Hasslacher and G. Doolen, *Los Alamos National Labs, Los Alamos, NM.* Recently discovered solutions to chemical reaction-diffusion equations are able to develop nanoscale chemical density patterns which can be used to construct structures using surfactants which assemble at the interface between chemical concentrations. The different types of solutions possible will be discussed along with proposed applications. Computer-generated videos illustrating the applications will be shown as well as videos of macroscopic experiments which track the simulations.

Fa3 Buried Structure for Coupled Electron Waveguides, F. Wakaya*, A. Nozawa*, J. Yanagisawa*, Y. Yuba*, S. Takaoka** K. Murase**,*** and K. Gamo*,***, * *Faculty of Engineering Science,* ** *Faculty of Science,* *** *Research Center for Extreme Materials, Osaka University, Toyonaka, Osaka 560, Japan.* Recently there has been much interest in mesoscopic structures. A coupled electron waveguide is one of the promising structures to realize future electronic devices, so that fabrication technologies and transport properties of such structures are attracting much attention of researchers. We have proposed a novel device structure for a coupled electron waveguide which is buried in GaAs/AlGaAs heterostructures, and developed the facility suitable for the fabrication of the device, which is composed of low energy focused ion beam (FIB) system and the molecular beam epitaxy (MBE) system coupled by an ultra high vacuum (UHV) tunnel. The basic structure of the device is two quantum wells grown by MBE. The Si is doped partially by *in-situ* implantation using low energy FIB, so that electrons exist only in part of the quantum well and quantum wires are formed. Consequently, two electron waveguides are coupled in the direction of the growth. The two waveguides can be much closer than the device fabricated by Schottky gate technique. The distance between two waveguides is very important to determine the transfer properties of an electron wave. The low energy is essentially important for reduction of damage. In order to reduce introduction of the surface and interface contamination during the growth interruption, which is required for the FIB implantation, the FIB and MBE coupled system is very promising. Electrostatic potentials, electron eigenfunctions and energy eigenvalues are obtained by solving Schrödinger equation and Poisson equation self-consistently. It is confirmed that a single mode waveguide can be realized using FIB with diameter of 50 nm if the dopant concentration is optimized. The motion of the wave packet produced from these eigenstates were simulated, and we calculated transport properties of the device such as transfer lengths and transfer coefficients numerically. It was found that complete switching of electron wave can be realized if the material parameter and structural para-meter are chosen carefully. In summary, we proposed a novel structure for a coupled electron waveguide buried in the heterostructure, which can be fabricated using the FIB-MBE combined system. We calculated electrostatic potentials and eigenstates of the device. Transport properties of the device such as transfer length and transfer coefficient are simulated using these eigenstates.

Fa4 Direct Patterning of SiO_2 by Carbon-Enhanced Vapor Etching*, J.M. Ryan, J. Allgair, M.N. Kozicki, and D.K. Ferry, *Center for Solid State Electronics Research, Arizona State University, Tempe, AZ 85287-6206.* Hydrofluoric acid (HF) in an aqueous solution will etch silicon dioxide at a rate of several microns per minute. In vapor form however, HF etches silicon dioxide at a rate of a few lengths of nanometers per minute. If carbon is present at the surface, the etch rate for the HF vapor increases by up to two orders of magnitude. By using an electron-beam in a contamination resist process, carbon is selectively deposited on the surface of the silicon dioxide. Results show a selective ratio (etch rate of exposed area to unexposed area) of greater than 100:1. The dose needed for this process is only on the order of tens of $\mu C/cm^2$. Continuous lines less than 100 nm wide have been patterned in silicon dioxide 50 to 100 nm thick.

* Work supported in part by ARPA through ONR.

Fa5 Tunneling and Anti-Crossing in Double Quantum Well Hetero-structures with In-Plane Magnetic Fields*, J.A. Simmons, S.K. Lyo, J.F. Klem, M.E. Sherwin, and N. Harff, *Sandia National Laboratories, Albuquerque, NM. 87185.* We report on our transport studies of double quantum well (QW) AlGaAs/GaAs hetero-structures for in-plane magnetic fields (B) at low temperatures (~0.3K). Tunneling in such structures is 2D-2D, and thus, because of the greater restrictions in k-space, exhibits much sharper features than the more commonly studied double barrier devices, where the tunneling is 3D-2D, suggesting device applications. In our device we use a 0.3 μm wide top-date to deplete the top QW only, and the four terminal source-drain resistance is measured as a function of in-plane B. Near the gate, a significant portion of the current tunnels from the top to the bottom well. A transmission line analysis yields the tunneling conductance $G_{tun}(B)$, without the need for thinning the sample nor contacting the two electron layers independently. Two sharp peaks in $G_{tun}(B)$ are observed, corresponding to the tangential intersection points of the two wells' Fermi circles, which are

displaced in k-space from one another by an amount proportional to B. The B-values of the peaks are in agreement with a simple geometrical model based on the conservation of momentum and energy.[1] Further, the magnitudes and widths of the tunneling peaks agree well with a recently developed linear response theory[2] which incorporates energy smearing due to finite intra-well scatter-ing times, and thus the experiment provides a new method of measuring the electron lifetime. Finally, using a second 0.3 μm wide gate located 2 μm away from the first, we demonstrate for the first time the control of tunneling on a sub-micron length scale. We have also studied the in-plane conductivity $G_{||}(B)$, and here report the first observation of a B-induced anticrossing in double QW structures. In an in-plane B, the dispersion curves of the two wells are displaced in k-space from one another by an amount proportional to B. When the coupling between the two QWs is sufficiently strong, the two dispersion curves exhibit an anticrossing at moderate B, along with its associated energy gap. The lower energy branch of the anticrossing is saddle-shaped and has a singularity in the density of states. When B is such that the Fermi level resides near the anticrossing, electrons participating in transport undergo a substantial increase in effective mass due to the strong distortion in the dispersion curve's curvature. In principle the effective mass at a given B can be controlled via the densities and coupling strength of the two wells. Our data on $G_{||}(B)$ as a function of the QWs' densities exhibits a notch in the conductivity at the anti-crossing point, with the B-position of the notch proportional to the sum of the square roots of the two QW densities, as expected. The behavior of $G(_{||}B)$ is independent on the angle θ between the electric field and in-plane B. This data is compared with the predictions of a new theory on the B-induced anti-crossing in double QW systems.[3] The possibility of observing negative differential resistance in such structures will also be discussed.

* Supported by the U.S. Dept. of Energy under Contract No. DE-AC04-94AL85000.

[1] H.P. Eisenstein *et al.*, Phys. Rev. B **44**, 6511 (1991).
[2] S.K. Lyo and J.A. Simmons, J. Phys.: Condens. Matter **5**, L299 (1993).
[3] S.K. Lyo, in preparation.

Fa6 Interference in the Nonlocal Shubnikov-DeHaas Effect in a GaAs/AlGaAs 2DEG*, N.F. Deutscher, J.M. Ryan, and D.K. Ferry, *Center for Solid State Electronics, Arizona State University, Tempe, AZ 85287-6206.* We have investigated the nonlocal Shubnikov-DeHaas oscillations in a two dimensional electron gas in a GaAs/AlGaAs heterostructure. The device was a standard Hall bar with a gate dividing the device. Measurements were made in a nonlocal configuration where the current path does not physically intersect the voltage leads. Our results show that the magnitude of the Shubnikov-DeHaas oscillations is significantly reduced at the leads separated from the current leads by a gate when compared to leads not separated by a gate, even when the gate is biased so that all edge channels are nominally transmitting. This indicates the decay length for conductance, and fluctuations, in the nonlocal geometry is greatly affected by the presence of the gate in a manner that distorts the Landau levels as they pass underneath.

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Engineering Foundation Conferences

SURFACES & INTERFACES OF MESOSCOPIC DEVICES

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